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of

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for

**Channel and Quality of Service Adaptation for
Multimedia Delivery Over Wireless Networks**

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Channel and Quality of Service Adaptation for Multimedia Over Wireless Networks

[0001] CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This non-provisional application claims priority to US Provisional Patent Application Serial No. 60/218,375, filed on July 13, 2000, which is incorporated herein by reference.

[0003] TECHNICAL FIELD

[0004] The present invention relates to transmission of data over a network, and is more particularly related to systems, methods, and program products for transmission of multimedia data to a wireless host through a network.

[0005] BACKGROUND

[0006] The first generation (1G) of mobile cellular communications systems were analog such as Advanced Mobile Phone Service (AMPS), Total Access Communications System (TACS), and Nordic Mobile Telephone (NMT). Primarily used for voice, they were introduced in the late 1970s and early 1980s. Starting in the 1990s, second generation (2G) systems such as GSM (Global System for Mobile Communications), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access) used digital encoding.

Current 2G mobile communication systems are mainly geared for speech traffic and operate in symmetric full-duplex fashion. Data rates and other quality of service parameters in these systems are the same in the uplink and downlink. Real-time media can seldom be served in a 2G wireless platform.

[0007] The third generation (3G) system is defined by the International Telecommunications Union (ITU) under the IMT-2000 global framework and is designed for high-speed multimedia data and voice. Its goals include high-quality audio and video transmission and advanced global roaming, which means being able to go anywhere and

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automatically be handed off to whatever wireless system is available (in-house phone system, cellular, satellite, etc.). In third generation systems, data traffic, as generated by IP-based information retrieval applications, is expected to dominate. Different kinds of applications can be served by 3G systems at a certain time instance.

[0008] The characteristics of different kinds of media vary dramatically. For real time media transmission, such as video and audio, low delay is required while some kinds of errors can be tolerable. On the other hand, for non-real time media transmission, such as web access and file download, reliability is required while some levels of latency can be tolerable. Based on the different characteristics of different media streams, there are various QoS (Quality of Service) levels that are required. A key problem in a system with several services and different QoS level requirements is the derivation of a combination of these quality criteria into a single performance measure or cost function, where the combination will allow a straightforward mathematical optimization formulation.

[0009] It would be an advance in the art to provide a technique for optimizing a system with several services having different QoS level requirements for multimedia delivery over a wireless network, such as a third generation Wideband-CDMA network.

[0011] A system, method, and program product provide a cross-layer multiple media streams delivery architecture for end-to-end optimization of quality in the support of different classes of QoS (Quality of Service) levels and provide a resource allocation scheme to allocate resources that are adapted to Wideband-CDMA (W-CDMA) channel platforms.

[0012] BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Generally, the same numbers are used throughout the drawings to reference like elements and features.

[0014] Figures 1a and 1b are block diagrams showing an end-to-end architecture for data transmission, including video data, over a 3G network, according to one aspect of the present invention.

[0015] Figure 1c is a block diagram of an example content server suitable for use in the data network, according to one aspect of the present invention.

[0016] Figure 1d is a block diagram of an example wireless host suitable for use in the data network, according to one aspect of the present invention.

[0017] Figure 2 depicts a delivery architecture used to support different classes of Quality-of-Service (QoS) levels for multiple services at a certain time instance in a third generation (3G) wireless platform for the delivery of multiple kinds of media over wireless channels.

[0018] Figure 3 depicts a Data Link Level Quality of Service Adaptation data and control flow chart, where an admission control module negotiates with the Radio Link Control (RLC) and Medium Access Control (MAC) sublayers of the Data Link Layer, as well as the Physical Layer (PHY) to determine an appropriate mode for delivery of multiple kinds of media over wireless channels using the architecture depicted in Figure 2.

[0019] Figure 4 depicts an Application Level Quality of Service (QoS) adaptation data and control flow chart, which includes channel adaptive error control and interleaving mechanisms.

[0020] Figure 5a is a flow diagram showing a detail view of the framework for multimedia delivery for multiple services transmission over a Wideband-CDMA channel between a mobile station and a base station.

[0021] Figure 5b is a block diagram of an implementation of a hybrid Unequal Error Protection (UEP)/delay-constrained ARQ scheme for PFGS delivery over a wireless 3G network.

[0022] Figure 6 depicts a fading channel model, where a transmitted signal is subjected to a Rayleigh-distributed amplitude factor to account for the effects of fading, and to which Gaussian white noise is added.

[0023] Figure 7 depicts a two-state Markov chain, which models the fading channel seen in Figure 6 considering the dependence between consecutive packet-losses, where “1” is the received state and “0” is the loss state.

[0024] Figure 8 is an example of a computing operating environment capable of implementing, either wholly or partially, an illustrative implementation of the invention.

[0025] Figures 9a and 9b show different 3G protocol stacks, where Figure 9a shows a control-plane protocol stack for a 3G network used for 3G-specific control signaling, and where Figure 9b shows a user-plane protocol stack for all information sent and received by a user and transported via the user plane with the user-plane protocol stack.

[0026] Figure 10 illustrates for a downlink, Transport Format Combination Indicator (TFCI) (TFCI) information, Transmission Power Command (TPC), and pilot symbols that are time-multiplexed with data symbols.

[0027] Figure 11 shows the Rate-distortion relation with different channel conditions.

[0028] Figure 12 shows the relationship of the channel protection level and the probability of transmission failure.

[0029] Figures 13a shows the probability of transmission failure versus re-transmission times, and Figure 13b shows the delay caused by an implementation of an Automatic Retransmission reQuest (ARQ) scheme versus re-transmission times.

[0030] Figures 14a and 14b show the general relations of distortion-complexity and complexity-power, where Figure 14a is a graph indicating the relation of distortion vs. MIPS and Figure 14b is a graph indicating the relation of MIPS vs. power consumption.

[0031] Figure 15 shows the rate-power relation for Progressive Fine Grain Scalability (PFGS) source decoding in a graph of consumption time (ms) vs. source rate (kbps).

[0032] Figure 16 shows the rate-power relation for RS decoding in a graph of consumption time (ms) vs. source symbol (k).

[0033] Figure 17 shows the rate-distortion relation with an implementation of a Forward Error Correction (FEC) scheme in a graph of distortion vs. source rate.

[0034] Figures 18a-18b show rate-distortion with an implementation of an ARQ scheme and delay caused by the implemented ARQ scheme, where Figure 18a is a graph of distortion vs. source rate and Figure 18b is a graph of delay vs. source rate.

[0035] Figure 19 shows the rate-distortion relation with an implementation of a hybrid UEP/delay-constrained ARQ scheme in a graph of distortion vs. source rate.

[0036] Figures 20a and 20b show the average peak signal to noise ratio (PSNR) for the MPEG-4 test sequence “Foreman” using three (3) tested schemes under different bit rates, where each of Figures 20a and 20b is a graph of PSNR vs. channel rate in kbps showing, respectively, high and low error channels.

[0037] Figures 21a and 21b show the average peak signal to noise ratio (PSNR) for the MPEG-4 test sequence “Foreman” using the three (3) tested schemes of Figures 20a-20b at 320 kbps, where each of Figures 21a and 21b is a graph of PSNR vs. frame number, respectively, for the high and low error case.

[0038] Figures 22a-22f show video frames from the MPEG-4 test sequence “Foreman” using the three (3) tested schemes of Figures 20a-20b in a comparison of the reconstructed 44th frame and the 50th frame of the sequence.

[0039] Figures 23a and 23b show a comparison of the results using the three (3) tested schemes of Figures 20a-20 at 256 kbps in the high error case.

[0040] Figure 24a and 24b show a comparison of the reconstructed 36th frame of the MPEG-4 test sequence “Foreman” in the high error case.

[0041] Figures 25a-25b show a comparison of the results of the MPEG-4 test sequence “Foreman” using the three (3) tested schemes of Figures 20a-20b at 320 kbps under the low error case, where Figure 25a is a graph illustrating computation time in ms vs. frames and Figure 25b is a graph illustrating PSNR vs. frames.

[0042] Figures 26a-26c show the reconstructed 42nd video frame from the MPEG-4 test sequence “Foreman” in the low error case.

[0043] DETAILED DESCRIPTION

[0044] A cross-layer media delivery architecture that supports different classes of QoS (Quality of Service) levels and a resource allocation scheme to allocate available resources, adapted to W-CDMA channel status, are provided and through which end-to-end optimal quality are achieved.

[0045] The architecture is useful for designing adaptive multimedia wireless networks, particularly for the Wideband-CDMA (W-CDMA) platform, which is a Third Generation (3G) technology that increases data transmission rates in the Global System for Mobile Communications (GSM) by using CDMA (Code Division Multiple Access) instead of Time Division Multiple Access (TDMA).

[0046] Four areas, as follows, are discussed for an implementation of a network design:

(a) Theory and methodologies that facilitate a cross-layer design of a channel and QoS level adaptive scheme for multimedia delivery over W-CDMA. Several different layers are addressed for an implementation, including the air interface or Physical Layer, the Medium Access Control (MAC) layer, the Radio Link Control Layer (RLC), the Network Layer, the Transport Layer, and the Application Layer. Each layer, as discussed below, is designed to be adaptable to various conditions.

(b) Accurate channel modeling that predicts or estimates network behavior.

(c) Different classes of QoS levels are supported in the delivery of multiple media streams.

(d) Dynamic resource management for multiple services in the cross-layer media delivery architecture that adaptively adjusts the behavior of each layer.

[0047] 1. W-CDMA Providing the Probability for Multi-Services Delivery

[0048] In an implementation of the Third Generation (3G) platform, simultaneous supporting for several services is provided in a single radio interface for a certain terminal. An example of this is generally illustrated in Figure 1a.

[0049] Turning to Figure 1a, a block diagram of an example of a 3G wireless network is presented within which the teachings of the present invention may be practiced, according to one example implementation. More specifically, Figure 1a illustrates a block diagram wherein one or more hosts 102, 104 (e.g., content servers) are coupled to provide data to one or more wireless hosts 118, 120 through a 3G wireless network 108 via wireless network components 114 and 116.

[0050] As used herein, hosts 102, 104 are each intended to represent any of a wide variety of computing devices which provide content to requesting users. According to one implementation, one or more of host 102, 104 is a content server, to stream media content to requesting users upon request. In this regard, hosts 102, 104 may well comprise a personal computing system, a server computing system, a media server farm, a KIOSK, thin client hosts, thick client hosts, and the like. According to one implementation, to be described more fully below, host 102, 104 invokes an instance of a content delivery application upon receiving a request for content from a requesting user. The host 102, 104 implements the channel and QoS adaptation for multimedia delivery in 3G wireless network 108, at least in part on feedback received from wireless host 118, 120. The cross-layer media delivery architecture implemented by hosts 102, 104 support different classes of QoS (Quality of Service) levels and a resource allocation scheme to allocate resources, adapted to W-CDMA channel status, at least in part, on information received from the wireless host 118, 120.

[0051] Wireless hosts 118, 120 are also intended to represent any of a wide variety of computing devices with wireless communication facilities. In this regard, wireless hosts 118, 120 may well comprise cellular telephones, digital wireless telephones, personal digital assistant (PDA) with wireless communication facilities, a personal computing system with wireless communication facilities, and the like. As will be developed more fully below, wireless host 118, 120 invokes an instance of an application to request and receive content from a host 102, 104. According to one aspect of the invention, wireless host 118, 120 identifies transmission problems (e.g., multipath, fading, high BER problems, etc.) in the wireless communication channel (e.g., 114, 116), and informs hosts 102, 104 of such wireless transmission problems via the schemes described herein.

[0052] The wireless 108 network is intended to represent a wide variety of such networks known in the art. In this regard, the wireless network 108 may well be comprised of a cellular telephony network, a third generation digital communication system network, a personal communication system (PCS) network, a digital cellular telephony network, a two-way paging network, a two-way radio network, a one-way broadcast radio network, a wireless local area network (WLAN) and the like. Similarly, the wireless communication channel between 114/116 and 118/120 is intended to represent any of a wide variety of wireless communication links such as, for example, a radio frequency (RF) communication link, an infrared (IR) communication link, and the like commonly associated with any of the wireless communication networks above.

[0053] Figure 1b is a block diagram of an example of a server in communication with a wireless client through a 3G wireless network. The server implements a distortion/power optimized resource allocation scheme in accordance with an implementation of the invention, described in Section 5 below, in the allocation of the available resources. The

wireless client communicates network throughput and error rate measurements back to the server. The server uses the network throughput and error rate measurements from the wireless client in its distortion/power optimized resource allocation scheme.

[0054] Figure 1c is a block diagram of an example content server 200 suitable for use in the data network as, for example, host 102, 104, according to one example embodiment. In accordance with the illustrated example implementation of Figure 1c, server 200 is generally comprised of control logic 202, a system memory 204, one or more applications 206, and a media component 208. As used herein, server 200 is communicatively coupled to a wireless network (e.g., 108) to provide a requesting user with media content. According to one implementation, an application 206 (e.g., streaming application) is selectively invoked to retrieve media content from some source (e.g., file, audio/video device, audio/video tape, etc.) into a local memory 204 for encoding and transmission to a requesting user via media component 208. In this regard, server 200 is intended to represent any of a wide variety of servers for streaming media content.

[0055] Control logic 202 selectively invokes and controls various functional elements of content server 200 in response to requests for content. According to one embodiment, control logic 202 receives a request for media content from a remote host (e.g., wireless host 118), and selectively invokes an instance of a content delivery application 206 (e.g., a media streaming application) along with the resources of media component 208 to satisfy the request for content. According to one implementation, media component 208 is one of a plurality of applications 206 available on content server 200.

[0056] As used herein, control logic 202 and system memory 204 are intended to represent any of a wide variety of such devices known in the art. In this regard, control logic 202 may well include one or more of a processor, a microcontroller, an application specific integrated

circuit (ASIC), a programmable logic device (PLD), a programmable array logic (PAL), and/or instructions which, when executed by one of the foregoing devices, implements such control logic. Similarly, memory 204 is intended to represent any of a wide variety of volatile and/or non-volatile memory such as, for example, random access memory, read-only memory, a hard disk, an optical disk, a magnetic tape, and the like.

[0057] As introduced above, media component 208 is selectively invoked by control logic 202 in response to a request for content from server 200. As shown, media component 208 is comprised of an Admission Control and Radio Resource Control (RRC) module 210, a Link Level Quality of Service (QoS) Adaptation module 212, an Application Level Quality of Service (QoS) Adaptation module 214, and a Distortion / Power Optimized Resource Allocation Module 216. Each of the modules 210-216 will be described below in conjunction with the descriptions of Figures 3-5b.

[0058] Figure 1d is a block diagram of an example wireless host 300 suitable for use in the data network, according to one aspect of the present invention. As used herein, wireless host 300 may well be used in a wireless network 108 as wireless host 118, 120. As introduced above, wireless host 300 is intended to represent a wide range of computing systems with wireless communication capability such as, for example, wireless telephony devices, PDA's with wireless communication capability, one- and/or two-way pagers, personal computing systems, and the like.

[0059] In accordance with the illustrated example embodiment of Figure 1d, wireless host 300 is generally comprised of control logic 302, memory 304, application(s) 306 and a media component 308, each coupled as shown. As above, each of control logic 302 and memory 304 are intended to represent such logic and memory as are typically found on such devices, and need not be described further. According to one example implementation,

applications 306 include an application for receiving and rendering content from a communicatively coupled server (e.g., 102, 104). According to one example, applications 306 include an Internet browser application that enables a wireless host to access and receive content (e.g., media content) from an Internet server (e.g., 102, 104).

[0060] When an application is invoked to access and receive content from a server (102, 104), control logic 302 invokes an instance of media component 308 to provide the requisite interface at the Transport Layer. In accordance with the illustrated example implementation of Figure 1d, media component 308 includes a Receiving Buffer/ DeMultiplexer (DeMux)/ Depacketizer / Post Processing module 310, a Channel Estimation: Network Throughput / Error Rate Measurement module 312, and a Quality of Service (QoS) Information Monitoring module 314. Each of the modules 310-314 will be described below in conjunction with the descriptions of Figures 5a and 5b.

[0061] Consider a scenario where a customer has a simultaneous voice or video call with Web browsing on the customer's wireless device. This is essentially an added value for the end-user. To support multiple services at a certain time instance, a third generation wireless platform adopts the architecture illustrated in Figure 2. One of the central building blocks of the 3G W-CDMA platforms is the multi-rate support provided by the Physical Layer. The Physical Layer is able to execute a change of data rate at multiple of the maximum frequency of 10 ms in a radio frame. Thus, the natural task of medium access control (MAC) is to select the combination to be applied based on offered load from a set of logical-channel inputs. The Radio Link Control (RLC) sublayer of the Data Link Layer provides segmentation and retransmission services for both user and control data. The Radio Resource Control (RRC) sublayer of the Network Layer handles all configuration operations

with peer-to-peer control signaling between the network and the terminal, and by acting as a management entity and configuring the operation of all lower layers.

[0062] The functions defined for RLC are specific to one logical channel, which is why the behavior of RLC is described through one entity as connected to one logical channel. The functions of MAC address either one common channel or one terminal including the operation on dedicated channels. Therefore, no functional entities specific to one stream of data are shown on MAC.

[0063] 2. Cross-Layer Architecture for Channel and QoS Level Adaptive Multimedia Delivery Over W-CDMA

[0064] Different broadband services require different amounts of bandwidth and have different priorities. For example, a connection for visual communications will in general require more bandwidth than one for data communications, and a voice connection will in general be of higher priority than either a data or a video connection. In response to these varied demands, the network designer may choose to assign different amounts of bandwidth to different types of traffic. The motivation for such an approach stems from the desire to support different kinds of multimedia services with a reasonable level of performance and without letting the demand from any one-type shutout other types of services. The challenge for the designer is to come up with techniques that are able to balance the needs of the various applications with the need of the system to accommodate as many connections as possible. This task of providing a guaranteed quality of service (QoS) level with high bandwidth utilization while servicing the largest possible number of connections can be achieved through a combination of intelligent admission control, bandwidth reservation and statistical multiplexing.

[0065] To effectively deliver multiple services over 3G W-CDMA channels, multiple stream support and QoS level differentiation should be addressed in the architecture. Multiple Stream Support is defined as the ability to simultaneously support streams with different QoS level requirements. This is important since multimedia communications between users may have components such as voice, video, and data with different QoS level requirements. QoS Level Differentiation is defined as the ability to provide various data rates and various Bit Error Rates (BERs) to higher Network Layers. This is desirable to support the QoS levels of higher network layers.

[0066] The third generation (3G) wireless standards define concepts that can support ranges of parameters values. This results in many alternative ways to map a set of traffic and QoS level parameters of the upper Application Layer to the lower layers for radio transmission. In the delivery architecture of one implementation, the QoS level adaptation is divided into two parts: A Data Link Level QoS Adaptation and an Application Level QoS Adaptation, each of which is discussed below.

[0067] 2.1 Data Link Level QoS Adaptation

[0068] To effectively deliver multiple kinds of media over 3G W-CDMA channels, different classes of QoS levels need to be supported in the delivery architecture. The quality of the transmitted stream is mainly related to its sending rate, latency, fault tolerance, level of protection, transmitted channel characteristics, etc. "Level of protection" is mentioned here because various data types differ in robustness and in the perceptual effects of errors. In the delivery architecture seen in Figure 3, an Admission Control and RRC module conducts a negotiation at the Radio Resource Control (RRC) Layer with the RLC and MAC sublayers of the Data Link Layer, and also with the Physical layer, as seen in Figure 2, to determine an appropriate QoS level supporting.

[0069] Figure 3 shows an Admission Control & Radio Resource Control (RRC) module that corresponds to the Admission Control and Radio Resource Control (RRC) module 210 seen in Figure 1c. Figure 3 also shows a Data Link Level QoS Adaptation module that corresponds to the Data Link Level Quality of Service (QoS) Adaptation module 212 seen in Figure 1c.

[0070] To support simultaneous multiple services delivery over a W-CDMA channel, each service is mapped into an individual transport channel. For an incoming service request, corresponding configuration needs are processed based on the characteristics of the service request. Latency, fault tolerance and level of protection requirements are passed from the source to the channel coding side. Then, a suitable interleaving length at the Physical Layer and a suitable retransmission count at the Radio Link Control (RLC) layer can be calculated based on the above requirements. Accordingly, as part of the module for the Data Link Level QoS adaptation, Figure 3 depicts the Adaptive Interleaving Length Selection module for the Physical Layer (PHY), and also depicts the Media Delay Bound Setting module for the Radio Link Control (RLC) layer.

[0071] A suitable channel encoding model as to a protection rate is selected based on the fault tolerance requirement in the Physical Layer. As an example, a $\frac{1}{2}$ convolutional code is selected for the video delivery and a turbo code is selected for the Web data application. The source encoder also controls the required level of protection, which in turn will affect the queue scheduling scheme in the MAC sublayer of the Data Link Layer as well as the error protection degree in the Application Layer.

[0072] By selecting the proper bit rates, transmitter powers, and the transmission schedule in each logical link, the aim is to maximize the total throughput defined as the sum of all (average) data rates in all the links that are currently active.

Variable	Mean	SD	Min	Max
Age	34.5	10.2	21	55
Gender	0.45	0.50	0	1
Marital status	0.65	0.48	0	1
Education	12.5	1.5	9	16
Income	15.2	8.5	5	35
Occupation	1.2	0.8	0	2
Health status	1.8	0.5	1	2
Stress level	2.5	1.2	1	4
Life satisfaction	3.2	0.8	2	4
Resilience	2.8	0.9	2	4
Optimism	3.5	0.7	2	4
Gratitude	3.8	0.6	2	4
Self-efficacy	3.1	0.9	2	4
Hope	3.4	0.8	2	4
Positive emotions	3.6	0.7	2	4
Negative emotions	2.2	0.6	1	3
Life events	1.5	0.8	0	3
Perceived stress	2.8	1.0	1	4
Coping strategies	2.5	0.9	1	4
Support systems	3.0	0.7	2	4
Quality of life	3.3	0.8	2	4
Overall well-being	3.5	0.7	2	4

[0075] Considering the limited bandwidth and varying error rate of the wireless link, it is important that the error control mechanism is efficient. To this end, the aim is to investigate the use of a channel adaptive hybrid error control mechanism as illustrated in Figure 4, where the amount of redundancy is kept to a minimum. Figure 4 shows an Application Level QoS Adaptation module that corresponds to the Application Level QoS Adaptation module 214 in media component 208 of server 200 seen in Figure 1c.

[0077] Notice that the FEC, or error control scheme, can be adapted to the instantaneous error rate, while ARQ is used to recover lost/corrupted packets which cannot be recovered

through FEC. Here there is a new kind of ARQ, which named delay-bounded ARQ. This is a limited retransmission ARQ protocol, i.e., if a packet does not arrive after certain time interval, it gives up and passes the loss to higher layers, as seen in the Delay Constraint Automatic Repeat Request (Hybrid ARQ) module of Figure 4.

[0078] In order to keep the FEC to minimum, the developed error control mechanism also takes the media coding characteristics into account. The amount of redundancy is selected by distinguishing the significance of the various media types and by determining the impact of error rate from each of the media types onto the overall media quality, as seen in the Channel Adaptive & Priority-sensitive Forward Error Control (Hybrid FEC) module of Figure 4.

[0079] The simulation results discussed in Section 9 show that this channel adaptive hybrid error control scheme with priority-sensitive redundancy provides better performance than other error control schemes.

[0080] 3. Channel and QoS Level Adaptive Multimedia Delivery Architecture

[0081] In summary, three typical characteristics are embodied in this delivery architecture:

- (i) Dynamically generate the feedback about the Bit Error Rate (BER)/ Forward Error Correction (FEC) protection level and delay. At the same time, accurately estimate the channel status.
- (ii) Periodically re-allocate the available resources to different kinds of media streams based on their media characteristics and the estimated channel status.
- (iii) Adaptively adjust the QoS level.

[0082] A major challenge in multimedia transmission over a W-CDMA channel is the joint consideration of the Network Layer control and the Application Layer control to achieve optimum end-to-end performance. To achieve the last mentioned sub-goal, cross-layer adaptation mechanisms have been designed in this framework, which are discussed in detail below, and are in-part summarized as follows:

- (a) adaptively spreading in the air interface to support various data rates for different media types;
- (b) adaptively selecting an encoding bit rate model and an interleaving length in the Physical Layer to satisfy the different latency and fault tolerance requirements of the different media types;
- (c) adaptively scheduling packets between multiple media streams in the Medium Access Control (MAC) sublayer of the Data Link Layer;
- (d) adaptively determining the retransmission times in the Radio Link Control (RLC) Layer based on the media latency characteristics of the media stream;

(e) adaptively selecting a transport protocol for different media streams.

Different media streams may adopt different kinds of transport protocol at the Transport Layer;

(f) adaptively selecting TCP protocol for the delivery of Web data and file data, and adaptively selecting a proposed UDP-like protocol for the delivery of other data, such as real time data including video and audio;

(g) adaptively allocating bits from the source encoder for a source bit stream and for Forward Error Correction (FEC) coding in the Application Layer based on the varying channel characteristics.

[0083] Giving a detailed view of the functionality of a multiple service transmission over a W-CDMA channel, mainly between a mobile station and a base station, Figure 5a depicts a framework of one implementation for multimedia delivery. Parts of the multimedia delivery framework will be described more detail in the following several Sections.

[0084] 4. Accurate Channel Modeling, Estimation and Dynamic Feedback Generation

[0085] To accurately estimate channel status for use in an error control scheme, a server in the network can monitor several channel-related characteristics on a near real-time basis on the fly. In the cross-layer architecture of one implementation, various layers are in charge of different kinds of feedback. Channel bit error rate (BER), frame error rate (FER), and the fading depth are fed back by the Physical Layer. Error type and transmission delay are fed back by the Data Link Layer. Location and handoff notification are fed back by the Network Layer. Besides this feedback information, a model can be adopted to accurately estimate the channel status.

[0086] Aiming at simulating wireless channels characterized by slow, highly-correlated-fading, a moderately slow motion of the mobile station is contemplated.

[0087] A channel model for one implementation is briefly depicted in Figures 6 and 7. As depicted in Figure 6, a transmitted signal $s(i)$ is first multiplied by a Rayleigh-distributed amplitude factor $a(i)$ taking into account the effect of fading, and then an Average Gaussian white noise (AWGN) factor $n(i)$ is added to the signal. The sequence of Rayleigh amplitude values is built by summing two squared Gaussian random variables $(x(i), y(i))$ and by taking the square root of the result. Channel correlation is taken into account by applying a low pass filter to the sequence of Gaussian values before squaring and summing them. The low pass filter used to account for channel correlation is built by assuming the speed of the mobile station. Given such a speed, the Doppler frequency f_{dopp} of the channel can be

$$\text{calculated through the formula } f_{dopp} = \frac{v_{mob}}{c_0} f_0, \quad (1)$$

where v_{mob} is the speed of the mobile station, c_0 is the speed of light, and f_0 is the carrier frequency.

[0088] For a broad range of parameters, the sequence of data-block success and failure can itself be approximated by means of a simple two-state Markov chain, seen in Figure 7, which can be used in modeling the fading channel seen in Figure 6. The two-state Markov chain, also known as the Gilbert Model, has “1” for the received state and “0” for the loss state. This model is able to capture the dependence between consecutive losses. Network packets can be represented as a binary time series, $\{x_i\}_{i=1}^n$, where x_i takes 1 if the i th packet has arrived successfully and 0 if it is lost. The current state, X_i , of the stochastic process depends only on the previous value, X_{i-1} . The transition probabilities between the two states are calculated as follows:

$$p = P[X_i = 1 | X_{i-1} = 0] \text{ and } q = P[X_i = 0 | X_{i-1} = 1]. \quad (2)$$

[0089] The maximum likelihood estimators of p and q for a sample trace are:

$$\hat{p} = n_{01}/n_0 \text{ and } \hat{q} = n_{10}/n_1, \quad (3)$$

where n_{01} is the number of times in the observed time series when 1 follows 0 and n_{10} is the number of times when 0 follows 1. n_0 is the number of 0s and n_1 is the number of 1s in the trace.

[0090] As seen in Figure 5a, two components that are considered with respect to the W-CDMA channel are the foregoing fading and Average White Gaussian noise (AWGN) factors discussed above.

[0091] Having generated a statistical model of the communication channel, the error control module can then employ one or more error control schemes to reduce the distortion being experienced.

[0092] 5. Resource Allocation Scheme

[0093] The three primary resources available for wireless access are bandwidth, space, and power. These resources must be allocated efficiently and dynamically in a mobile wireless environment. The objective of resource allocation in wireless networks is to decide how to allocate resources such that quality of service (QoS) level requirements of the applications requiring by the multimedia streams can be satisfied.

[0094] To design an efficient resource allocation scheme, several difficulties should be taken into consideration. First, due to the multi-path fading effect, the wireless channel is time varying. Second, the radio bandwidth and power are scarce resources. Third, multiple classes of traffic have different data rates and bit error rate requirements. To cope with all

these problems, the proposed scheme needs to be adaptive, efficient, flexible, and able to minimize the transmitted power, while satisfying the application QoS requirements .

[0095] The resource allocation problem is a special case of the general problem of decentralized dynamic decision-making. A well-developed theoretical foundation for this general problem is currently lacking. A general desire in a resource allocation mechanism is the minimization of the overall distortion, thus gaining the optimized quality of the global streams. One can denote the sending rate of i th media stream by r_i , the distortion that will be obtained in this stream can be denoted by d_i , and the quality impact degree of this stream can be denoted by α_i . Such a problem can be expressed as: Minimize $D = \sum_i \alpha_i \times d_i$, subject to $R = \sum_i r_i \leq R_T$, where R_T is the total bit budget for the W-CDMA channel, which is 384 kbps in wide area with high mobility and 2Mbps in a local area.

[0096] Each media has its own rate and distortion relationship: $R_i = F(D_i)$. The above optimization problem relies on this Rate and Distortion (R-D) function. Considering the unique wireless link characteristics such as bit error rate and fading depth, the corresponding R-D function has to be modified to account, in the wireless link, for distortion comprising the source distortion and the channel distortion. To this end, there is derived an R-D function for the MPEG-4 Progressive Fine Granular Scalability (PFGS) scalable codec, and an implementation that dynamically allocates bits between the source bit stream and the channel coding. A discussion follows of the R-D function for resource allocation for 3G networks, given the rate-distortion function in the context of error rate and throughput measurements.

[0097] An implementation, an example of which is seen in Figures 1b and 5b, is proposed for a distortion-minimized resource allocation and a power-minimized resource allocation

with a hybrid delay-constrained ARQ and Unequal Error Protection (UEP) for video transmission over a 3G wireless network, based on the measurements of throughput and error rate for the 3G wireless network. The architecture seen in Figures 1b and 5b has the components of the network throughput/error rate measurement and distortion/power optimized resource allocation, each of which is discussed below.

[0098] In the discussion that follows, measurements of throughput and error rate for a 3G wireless network are presented in Section 6. Section 7 presents preliminaries for a QoS level adaptive resource allocation. In Section 8, an implementation of distortion-optimized and power-optimized resource allocation schemes are presented, which schemes consider varying media characteristic and adapt to channel condition. Section 9 gives simulation results of the implementations discussed herein.

[0099] 6. Measurements Of Error Rate And Throughput In A 3G Network

6.1 Protocol stack of 3G network

[0100] A typical protocol stack for a 3G network is shown in Figures 9a and 9b, consisting of a control-plane stack in Figure 9a and a user-plane protocol stack in Figure 9b. The control plane is used for 3G-specific control signaling. More specifically, GMM/SM/SMS is in charge of general mobility management, session management, and short message services, respectively. The Radio Resource Control (RRC) sublayer of the Data Link Layer interacts with lower layers to provide local inter-layer control services, such as determining the transport format combination set (TFCS), for efficient usage of transport channels.

[0101] All information sent and received by a user is transported via the user plane. Application data is first packetized and then transported using the TCP/UDP transport protocol. For multimedia delivery that is discussed herein, UDP protocol is used. It shall be assumed that the UDP packet size is L_U bytes including the header information.

[0102] In between the UDP of the Transport Layer and the Data Link Layer, and within the Network Layer, there is the Internet Protocol (IP) sublayer, the Point-to-Point Protocol (PPP) sublayer, and the Packet Data Convergence Protocol (PDCP) sublayer.

[0103] The Radio Link Control (RLC) sublayer of the Data Link Layer provides three types of modes for data delivery, among which, the transparent mode transmits higher layer Protocol Data Units (PDUs) only with segmentation/reassembly functionality. The unacknowledged mode transmits higher layer PDUs without guaranteeing delivery but with a user-defined maximal number of retransmissions. The acknowledged mode transmits higher layer PDUs with guaranteed error-free delivery. Considering the multimedia characteristic, the transparent and unacknowledged modes are discussed for one implementation. The length of an RLC data unit, called a frame, is of L_L bytes. Thus, a UDP packet is segmented into $N_L = \left\lceil \frac{L_U}{L_L} \right\rceil$ RLC frames for transmission. The number of retransmissions allowed for a failed RLC frame is denoted as N_R .

[0104] The Medium Access Control (MAC) sublayer of the Data Link Layer functions in the selection of an appropriate transport format for each transport channel according to the instantaneous source rate. The transport format defines the transport block size (size of the RLC frame in transparent and unacknowledged modes), the transport block set size, the transmission time interval (TTI), the error detection capability (size of CRC), the error protection (channel coding) rate, etc. On the receiver side, after decoding the Transport Format Combination Indicator (TFCI) information, users can obtain the bit rate and channel decoding parameters for each transport channel.

[0105] The Physical Layer (PHY) offers information transfer services to the MAC sublayer of the Data Link Layer and also to higher layers. One of the main services provided by the

Physical Layer is the measurement of various quantities, such as the physical-channel bit error rate (BER), the transport-channel block error rate (BLER), the transport-channel bit rate, etc. In the Physical Layer, each physical channel is organized in a frame structure, which consists of 16 slots. For the downlink, TFCI, TPC (Transmission Power Command) and pilot symbols are time-multiplexed with data symbols, as seen in Figure 10. On the receiver side, once a slot is received, pilot symbols are used to estimate the channel status. With the prior known pilot information, channel estimation can be performed through some filtering techniques such as a weighted multi-slot average (WMSA) filter, a Gaussian filter, and a Wiener filter. Then, the Bit Error Rate (BER) of the physical channel before channel decoding can be calculated. At the end of each TTI, TFCI information is decoded. With the TFCI information, the channel decoding parameters of each transport channel is obtained, and in the meanwhile, the bit rate (B_{trans}) of each transport channel can be computed. Based on the error detection capability (CRC) evaluation of each transport block, the average Block Error Rate (BLER), P_{BL} , of the transport channel can be estimated. All these measured information are reported to the higher Data Link Layer for system performance analysis.

[0106] 6.2 RLC frame model of correlated fading channel

[0107] The traditional metric used for characterizing channel errors is average bit error rate or the average Block Error Rate (BLER), P_{BL} . After obtaining P_{BL} , there still exists a need for selecting an appropriate model to analyze the system performance in the Data Link Layer. A first-order Markov process can be used in modeling a transmission on a correlated Rayleigh fading channel as was summarized in Section 4, above, in reference to Figures 6 and 7. As seen in Figure 5a, two components that are considered for the W-CDMA channel

are the fading and the Average White Gaussian noise (AWGN) factors discussed in Section 4, above.

[0108] A sequence of transport blocks' successes and/or failures can be approximated by a two-state Markov chain, which is defined by the transition matrix

$$[0109] \quad M(x) = \begin{pmatrix} p(x) & r(x) \\ s(x) & q(x) \end{pmatrix} = \begin{pmatrix} p & 1-p \\ 1-q & q \end{pmatrix}^x, \quad (4)$$

[0110] where p and $1-q$ are the probabilities that the j^{th} transport block transmission is successful, given that the $(j-1)^{th}$ transport block transmission was successful or unsuccessful, respectively. Using this model, the steady-state transport block error rate, P_{BL} , is given by

$$P_{BL} = \frac{1-p}{2-p-q}. \quad (5)$$

[0111] For a Rayleigh fading channel with fading margin F , the average transport block error rate BLER, P_{BL} , and the Markov parameter (q) can be expressed as $P_{BL} = 1 - e^{-1/F}$ (5)

$$\text{and } q = 1 - \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{1/F} - 1}, \quad (6)$$

$$\text{where } \theta = \sqrt{\frac{2/F}{1-\rho^2}}. \quad (7)$$

[0112] In Eq. (7), $\rho = J_0(2\pi f_d T)$ is the correlation coefficient of two successive samples (spaced by T seconds, which equals 10 ms, 20 ms, 40 ms, or 80 ms in 3G network) of the complex Gaussian fading channel, f_d is the Doppler frequency that is equal to the mobile velocity divided by the carrier wavelength. $J_0(\cdot)$ is the Bessel function of the first kind and zero order, and $Q(\cdot, \cdot)$ is the Marcum-Q function given by:

$$Q(x, y) = \int_y^\infty e^{-\frac{(x^2+w^2)}{2}} I_0(xw) w dw. \quad (8)$$

[0113] Thus, the relationship between block error rate and Markov parameter can be easily represented as follows:

$$q = 1 - \frac{(1 - P_{BL}) \times (Q(\theta, \rho\theta) - Q(\rho\theta, \theta))}{P_{BL}}, \quad (9)$$

$$\text{where } \theta = \sqrt{\frac{-2 \log(1 - P_{BL})}{1 - J_0^2(2\pi f_d T)}}. \quad (10)$$

[0114] Notice that, in order to use this approximation approach to compute p and q , there is a need to compute the average transport block error rate, P_{BL} , which depends on the details of the modulation/coding scheme. One can obtain this information at the end of each TTI in a 3G network. Another factor that will affect the Markov parameter is the velocity of the mobile station. The decimation method and the statistical analysis of receiving signal method can be used to estimate the velocity of the mobile station.

[0115] 6.3 Throughput measurement

[0116] RLC in a 3G network supports the transparent, unacknowledged, and acknowledged modes of operations. The upper-layer packet is segmented into small RLC frames, and different retransmission policies are adopted for different RLC modes. The performance measurement of interest is the end-to-end throughput considering the interaction of RLC and the upper layer, which in one implementation is the UDP.

[0117] In one implementation, the unacknowledged RLC mode is used. One can denote the number of retransmissions allowed for a failed RLC frame as N_R , and the number of RLC frames per UDP packet as N_L . When the RLC sublayer of the Data Link Layer finds a frame error, it sends back a NACK requesting retransmission of the corrupted frame. RLC will abort the attempt after N_R unsuccessful retransmissions and pass the frame to the UDP of the

Transport Layer. Note that, so long as one RLC frame is lost in a UDP packet, the entire UDP packet is discarded.

[0118] As mentioned above, TFCI information is decoded at the end of each TTI on the receiver side. With the transport block set size, TTI, and other related information obtained by TFCI, the total bandwidth used for each transport channel (B_{trans}) can be calculated. To accurately estimate the available throughput in the Application Layer, the status of successive UDP packets are analyzed. Let $P_{u,ss}$ and $P_{u,fs}$ be the probabilities that the current UDP packet is successful given that the previous UDP packet was successful or not. Further let $P_{u,sf} = 1 - P_{u,ss}$ and $P_{u,ff} = 1 - P_{u,fs}$. Then, the available UDP throughput can be defined as

$$AUB = B_{trans} \times \frac{1 - P_{u,ff}}{2 - P_{u,ss} - P_{u,ff}} = B_{trans} \times \frac{1 - P_{u,fs}}{1 + P_{u,fs} - P_{u,ss}}. \quad (11)$$

[0119] To calculate the packet transition probabilities, several denotations are introduced.

Let $P_{ul,sf}^{(n)}$ be the probability that the last RLC transmission of the current UDP packet with n RLC frames is successful given that the current UDP packet is a failure, let $P_{ul,ss}^{(n)}$ be the probability that the last RLC transmission of the current UDP packet with n RLC frames is successful given that the current UDP packet is a success, let $P_{lu,sf}$ be the probability that the current UDP packet is failed given that last RLC transmission of the previous UDP packet was a success, and let $P_{lu,ff}$ be the probability that the current UDP packet is failed given that last RLC transmission of the previous UDP packet was a failure. Then, the UDP packet transition probabilities can be represented as

$$P_{u,ss} = (1 - P_{lu,sf})P_{ul,ss}^{(N_L)} + (1 - P_{lu,ff})(1 - P_{ul,ss}^{(N_L)}) \quad (12)$$

$$\text{and } P_{u,fs} = (1 - P_{lu,sf})P_{ul,sf}^{(N_L)} + (1 - P_{lu,ff})(1 - P_{ul,sf}^{(N_L)}), \quad (13)$$

where $P_{ul,ss}^{(n)} = 1$, for any n , and $P_{ul,sf}^{(n)}$ can be derived in a recursive way as follows:

$$P_{ul,sf}^{(n)} = P_{ul,sf}^{(n-1)} (p + (1-p) \times \sum_{j=0}^{N_R} q^j \times (1-q)) + (1 - P_{ul,sf}^{(n-1)}) (\sum_{j=0}^{N_R} q^j \times (1-q)). \quad (14)$$

[0120] To represent $P_{lu,sf}$ and $P_{lu,ff}$, another two denotations are introduced. Let p_n be the probability that at least 1 out of n RLC frames fails given that the first RLC transmission was a success. Let $q_n^{(k)}$ be the probability that at least 1 out of n RLC frames fails given that the first RLC frame already had $k \leq N_R$ retransmissions and current RLC transmission is a failure. Then there is obtained:

$$P_{lu,sf} = p \times p_{N_L} + (1-p) \times q_{N_L}^{(0)} \quad (15)$$

$$\text{and } P_{lu,ff} = (1-q) \times p_{N_L} + q \times q_{N_L}^{(0)}, \quad (16)$$

$$\text{where } p_n = p \times p_{n-1} + (1-p) \times q_{n-1}^{(0)} \quad (17)$$

$$\text{and } q_n^{(k)} = (1-q) \times p_{n-1} + q \times q_{n-1}^{(k+1)}.$$

[0121] Notice that the terminating conditions for the above recursive relation are $p_1 = 0$,

$$q_n^{(N_R)} = 1, \text{ and } q_1^{(k)} = q^{(N_R-k)}.$$

[0122] Up to now, the relationship between the available UDP throughput and RLC frame transition probabilities had been derived. After a user-defined time interval, all the performance measurement information, such as available UDP throughput, frame/packet transition probabilities, BER/BLER, etc., are reported to the Application Layer. The resource allocation for multimedia transmission then can be performed based on the provided information.

[0123] 7. PRELIMINARIES FOR QOS Level ADAPTIVE RESOURCE ALLOCATION

[0124] A discussion that follows is of rate-distortion and rate-power consumption relations for a source coder and for a channel coder. Since a video-streaming scenario is considered in one implementation, a focus will be placed upon the source decoding and channel decoding in the following sections.

[0125] 7.1 Rate-distortion relation for source and channel coding

[0126] Most existing video source coders are optimized to achieve the best performance at a certain rate while assuming that all of the coded bits are correctly received. When video media is delivered over a wireless channel, the channel transmission error in the random location causes additional channel distortion. Thus, there is defined end-to-end performance using the expected end-to-end distortion, D_T , which is composed of the source distortion and the channel distortion. Mathematically, $D_T = D_s + P_{fail} \times D_c$, where D_s is the source distortion that is caused by the video rate control, D_c is the channel distortion resulting from random transmission error and burst-fading error, and where P_{fail} is the probability that a video packet transmits unsuccessfully. Notice that P_{fail} is related to the channel bit error rate (BER) and bursty length. As seen from Figure 11, different channel conditions may have different impacts on the expected end-to-end distortion. That is,

$$(BER_1 \neq BER_2) \& (R_1 \neq R_2) \Rightarrow \Delta D_1 \neq \Delta D_2.$$

[0127] In one implementation, source is encoded by a layered scalable coder, e.g., MPEG-4 PFGS video coder, which can generate bit rates anywhere from tens of kilobits to a few mega bits per second with arbitrarily fine granularity. An example of this encoding is seen in Figure 5b where raw data, such as raw video, is input to a PFGS Source Encoder. The

raw video is encoded into two parts: one part is called base layer (BL) that carries the most important information, such as motion vector information, etc., while the other part is a plurality of called enhancement layers (ELs) that carry less importance information.

Furthermore, layers of the same frame in PFGS are correlated. Specifically, the higher layer information relies on the corresponding one in the lower layers. On the receiver side, if any residual error occurs in the lower layers, the corresponding information bits in the higher layers will be discarded whether they are correct or not. Thus, the expected end-to-end distortion of PFGS can be represented as

$$D_T = D_s + \sum_{j=1}^L \left\{ \sum_{m=1}^{n_j} D_{c,packet}(m, j) \times [P_{fail,packet}(m, j) | \prod_{i=1}^{j-1} (1 - P_{fail,packet}(m, i))] \right\}, \quad (18)$$

where L represents the number of layers that can be delivered, n_j denotes the number of packets in the j^{th} layer, $D_{c,packet}(x, y)$ represents the channel distortion caused by loss of the x^{th} packet in the y^{th} layer, and $P_{fail,packet}(x, y)$ is the probability that the x^{th} packet in the y^{th} layer is lost. Notice that the dependency relationship among different layers is embodied by the conditional probability as expressed in Eq. (18).

[0128] Next a discussion will be had of rate-distortion caused by a channel decoder including FEC and ARQ. In one implementation, Reed-Solomon (RS) codes are used for FEC. The RS codes are used because of their abilities to correct channel burst errors, which are common in a wireless channel. An RS code is represented as $RS(n, k)$, where k is the length of source symbols and $n-k$ is the length of protection symbols. It is known that an RS code usually can correct up to $t = \left\lfloor \frac{n-k}{2} \right\rfloor$ symbol errors. The failure probability of an $RS(n, k)$ code is defined as:

$$P_{fail} = 1 - \sum_{j=0}^t P(n, j), \quad (19)$$

$$[0129] \quad P(n, j) = \sum_{i=0}^j \binom{n}{i} p_s^i (1 - p_s)^{n-i}, \quad (20)$$

$$[0130] \quad p_s = 1 - (1 - p_b)^m, \quad (21)$$

$$[0131] \quad \text{and } p_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \quad (22)$$

[0132] where $P(n, j)$ represents the probability of less than j symbol errors occurs in the n symbol's transmission, p_s is the probability of symbol transmission error, m is the number of bits per symbol, p_b is the bit-error probability, E_b is the fixed power per bit, and $N_0/2$ is the channel noise variance.

[0133] Based on the above analysis, it can be deduced that increasing channel protection can reduce possible channel errors, which in turn decreases the end-to-end distortion. That is, $t_2 > t_1 \Rightarrow P_2 < P_1$, as shown in Figure 12.

[0134] As for ARQ, selective retransmission is adopted as retransmission policy in one implementation. In this implementation, only the loss/corrupted packets would be retransmitted across the channel. Notice that retransmission of corrupted data introduces additional delay, which is desirable for real-time applications. Therefore, in real-time media delivery, the delay bound of media should be considered as a constraint for retransmission.

[0135] The probability of packet transmission failure after the n^{th} retransmission is defined

$$\text{as: } P_{fail, packet}^{(n)} = (1 - P_{s, packet})^n \quad (23)$$

$$\text{and } P_{s, packet} = (1 - p_b)^{len}, \quad (24)$$

where $P_{s, packet}$ is the probability that the packet can be correctly transmitted, and len is the number of bits in the packet. Suppose N_{max} is the maximum number of times for

retransmission of a certain packet, the rate needed for the packet transmission can be

$$\text{represented as: } R = R_s + \sum_{i=1}^{N_{\max}} P_{fail}^{(i)} \times R_s. \quad (25)$$

[0136] Based on the above analysis, with the higher retransmission times, a lower probability of transmission failure can be obtained, thereby causing larger delay. This is plotted in Figures 13a and 13b.

[0137] 7.2 Rate-Power Consumption For Source And Channel Coding

[0138] The total power consumed in a system consists of communication power and processing power. For the source part on the receiver side, the communication power refers to the source receiving power, which is relatively small compared with the source processing power and is only related to the received source bit rate, while the processing power is the power consumed for source decoding. For simplicity, complexity is used in one implementation to represent the processing power consumption. To be specific, the more complex an algorithm is, the more processing power would be consumed. Coding standards are, in general, compromises between computational complexity and performance.

Specifically, with higher complexity, smaller distortion can be achieved, and vice versa.

[0139] Figures 14a and 14b depict the general description of the relationship between distortion and complexity as well as the relationship between complexity and processing power consumption. It can be seen that with higher complexity, smaller distortion can be achieved, while with higher complexity, more processing power will be consumed. That is,

$$C_2 > C_1 \Rightarrow D_2 < D_1 \text{ and } C_2 > C_1 \Rightarrow P_2 > P_1.$$

[0140] In one implementation, the CPU computation time is used to measure the complexity of the decoding algorithm. Specifically, for PFGS source decoding, the processing power consumed in the base layer (BL) mainly consists of motion compensation, inverse discrete

transform (IDCT), and quantization, while the processing power consumed in the enhancement layers mainly consist of IDCT and quantization. The rate-power relation for PFGS source decoding is illustrated in Figure 15. An example of PFGS source decoding is seen in Figure 5b where the BL Channel Decoding and EL Channel Decoding are input to a PFGS Decoder for output within a wireless client.

[0141] Similar to the source part, the communication power consumed by the channel code-decode (codec) on the receiver side refers to the channel receiving power, which is related to the received channel protection rate, while the processing power is the power consumed for channel decoding. Compared with the channel receiving power, processing power is dominated in power consumption in channel decoding. The majority of the processing power consumption by the RS codec is due to the RS decoder. The energy consumption for decoding an $RS(n, k)$ code per codeword is:

$$\varepsilon_{dec/codeword} = (4tn + 10t^2)\varepsilon_{mult} + (4tn + 6t^2)\varepsilon_{add} + 3\varepsilon_{inv}, \quad (26)$$

[0142] where ε_{mult} , ε_{add} , and ε_{inv} represent the energy consumed in the $m \times m$ -bit multiplier, m -bit addition, and m -bit inversion, respectively. Similar to the source side, the computation time is used to represent the consumed processing power of the channel. The rate-power relation for RS decoding is depicted in Figure 16.

[0143] 8. QOS LEVEL ADAPTIVE RESOURCE ALLOCATION FOR SCALABLE VIDEO TRANSMISSION OVER 3G WIRELESS NETWORKS

[0144] Channel performance measurement was discussed in Section 6, above. The problem now to be discussed in this Section 8 is how to efficiently utilize the limited channel capacity. According to the analysis in the previous Section 7, above, both source coding by a source encoder and channel coding by a channel encoder will occupy certain

portion of resources (e.g., bits and processing power), thereby making different contributions to the end-to-end QoS level, such as distortion, delay, and power consumption. The study of resource allocation in this Section 8 is to address the problem of finding the optimal distribution of resources among a set of competing subscribers (e.g., source coder and channel coder) that minimizes the objective function, such as distortion or power consumption, subject to total resource constraints and / or QoS level requirements. An example of resource allocation is seen in Figure 5a, where the server implements a Resource Allocation module that includes the Rate-Quality relation, Buffer Control, Power Control, and Handoff notification to be fed back via the Network Layer.

[0145] In one implementation of a resource allocation scheme, the objective function O is the sum of an individual subscriber's objective function o_i , subject to the sum of the individual subscriber's required resource r_i , which would not exceed the resource limit R , and/or the sum of the individual subscriber's QoS level requirement q_i , which would not exceed the total QoS level requirement Q . Mathematically,

$$\min_{\{q_i, \text{ and/or } r_i\}} O = \sum_{i=1}^N o_i(q_i, r_i)$$

$$\text{subject to } \sum_{i=1}^N q_i \leq Q \text{ and/or } \sum_{i=1}^N r_i \leq R, \quad (27)$$

where N is the number of subscribers.

[0146] In one implementation, resource distribution between the PFGS source coder and the channel coder is based on the above formulation. From the rate-distortion relation analyzed in the previous section, it is essential to adopt some error protection schemes so as to reduce the distortion caused by channel transmission. FEC is suited for real-time communications, but varying channel condition limits its effective use, because a worst-case design may lead to a large amount of overhead. Once the channel condition is known, adaptive FEC can be

adopted to meet the channel condition. Specifically, if the network condition is good, the error correction rate will be reduced. On the other hand, if the network condition is bad, the error correction rate will be increased. As shown in Figure 17, there exists an optimal rate ($R_{opt-FEC}$) for FEC scheme to achieve the minimal distortion ($D_{min-FEC}$).

[0147] Closed-loop error control techniques such as ARQ have been shown to be more effective than FEC. But retransmission of corrupted data frames introduces additional delay, which is critical for real-time services. As shown in Figures 18a and 18b, there exists an optimal rate ($R_{opt-ARQ}$) for ARQ scheme to achieve the minimal distortion ($D_{min-ARQ}$). It can be seen that $D_{min-ARQ} \leq D_{min-FEC}$. However, in real-time applications such as conferencing and streaming, the delay constraint had to be considered. When considering media's delay constraint (T_{bound}), the optimal distortion, $D_{min-ARQ}$, cannot be guaranteed to be achieved. Therefore, a hybrid FEC and a delay-constrained ARQ are introduced as the error protection scheme for multimedia delivery.

[0148] 8.1 Hybrid UEP and delay-constrained ARQ for scalable video delivery

[0149] Figure 5b is a block diagram of an example of a server in communication with a wireless client through a 3G wireless network. Figure 5b is an expansion upon the architecture seen in Figure 1b. The server implements a distortion and power optimization scheme in accordance with an implementation of the invention, described in Section 5 above, in the allocation of bits. The wireless client communicates retransmission requests back to the server. The server uses the retransmission requests from the wireless client in its distortion and power optimization scheme.

[0150] The server also implements a hybrid UEP and delay-constrained ARQ scheme for scalable video delivery in which the server transmits a response to a service request for a multimedia stream to the wireless client over the 3G wireless network. In this scheme, Base

Layers (BL) and Enhancement Layers (EL) are protected differently. Because the BL carries the significant information, it should be transmitted in a well-controlled way to prevent the quality of reconstructed video from degrading severely. Therefore, strong error protection codes are added for BL. Note that how much protection should be added to the BL is based on the channel condition and available resources. As analyzed above, FEC usually incurs overhead, and the ARQ scheme is usually more efficient than FEC provided certain delay is allowed. As a result, there is adopted a hybrid delay-constrained ARQ and FEC for the BL error protection.

[0151] The Hybrid ARQ and Hybrid FEC of Figure 5b are depicted contextually within the Application Layer Quality of Service Level Adaptation scheme seen in Figure 4. The Power / Distortion Optimized Bit Allocation module seen in Figure 5b is depicted contextually within the Distortion / Power Optimized Resource Allocation module 216 of server 200 seen in Figure 1c, and represents an implementation of the functionality of the Resource Allocation module of the Server seen in Figure 5a.

[0152] A discussion follows of the operation of the hybrid delay-constrained ARQ and FEC for the BL error protection. On the sender side, based on the delay constraint $D_{constrained}$ that is limited by video frame rate, current roundtrip transmission time RTT , and the estimated time consumed by processing procedure $D_{processing}$, the maximum number of transmissions

for current packet N_{max} can be calculated as follows:
$$N_{max} = \frac{D_{constrained} - D_{processing}}{RTT}.$$

(28)

[0153] Then, the sender determines the level of protection for each transmission such that the required residual error rate is within the desired range and the overhead is minimized.

[0154] As for ELs, different levels of error protections are added to the different layers. This is because error occurring in the lower layer may heavily corrupt the corresponding higher layers in the same frame and thus affect several subsequent frames. In other words, a bit error would result in error propagation. As a result, the bandwidth for higher layers is wasted, and in the meanwhile, the video quality is deteriorated. Note that, in order to efficiently add error protection to ELs, the sender determines the degree of protection for each layer adapting to the current channel condition for achieving the minimal objective function under the required QoS level and resource constraints.

[0155] Figure 5b illustrates one implementation of the scheme. The 3G network performance is first dynamically measured. Total available throughput, bit/frame/packet error rate, and some other network related information are fed back to the sender. Given the network information, optimal resource allocation is then performed to achieve the minimal objective (e.g., distortion or power consumption). The channel decoder reconstructs packets through a channel decoding process. For ELs, the output of the channel decoder is directed for source decoding; while for BLs, if residual error still exists, the receiver decides whether to send a retransmission request based on the delay bound of the packet. If the delay bound has expired, the request will not be sent. Otherwise, when receiving a retransmission request, the sender only transmits a necessary higher protection part for the corresponding packet.

[0156] In summary, the proposed error protection scheme is aimed to achieve adaptiveness and efficiency within the constraint of the bounded delay. However, the hybrid UEP and delay-constrained ARQ protection scheme poses a challenging resource allocation problem, because one has to consider two issues simultaneously: the tradeoff of allocation between

the source and channel codes and the tradeoff between forward error protection and retransmission.

[0157] 8.2 Distortion-minimized Resource Allocation

[0158] Channel bandwidth capacity is highly limited in wireless networks. The allocation on the source side has a tradeoff between the source coding rate and the source distortion, the FEC has a tradeoff between the error protection rate and the channel distortion, and the ARQ has a tradeoff between the retransmission times and the channel distortion. Therefore, the allocation of the bits among the source, the FEC, and the ARQ for a given fixed bandwidth capacity are focused upon so as to achieve the minimal expected end-to-end distortion.

[0159] Suppose $R(t)$ is the available bit rate at time t , $R_S(t)$, $R_{ARQ}(t)$, and $R_{FEC}(t)$ are the bit rates used for the source, the FEC, the ARQ at time t , respectively. Then the distortion-minimized resource allocation can be formulated as

$$\begin{aligned} \min_{\{R_S, R_{ARQ}, R_{FEC}\}} D_{end-to-end} &= D_S(R_S) + D_{ARQ}(R_{ARQ}) + D_{FEC}(R_{FEC}) \text{ subject to} \\ R_S(t) + R_{ARQ}(t) + R_{FEC}(t) &\leq R(t), \end{aligned} \quad (29)$$

where $D_S(R_S)$ is the source distortion caused by source coding rate R_S , $D_{ARQ}(R_{ARQ})$ and $D_{FEC}(R_{FEC})$ are the residual channel distortions caused by applying retransmission rate R_{ARQ} and error protection rate R_{FEC} , respectively.

[0160] The bit rate of the source side is composed of bit rate in both the BL and ELs.

$$\text{Mathematically, } R_S = R_{S_base} + \sum_{l=1}^L R_{S_enh}(l), \quad (30)$$

where L is the number of layers in ELs, and R_{S_base} and R_{S_enh} represent the source rates of the BL and of ELs, respectively.

[0161] Source distortion is composed of distortion in both the BL and ELs, which can be

$$\text{described as } D_s(R_s) = D_s(R_{s_base}) + \sum_{i=1}^L D_s(R_{s_enh}(i)). \quad (31)$$

[0162] Next, a discussion is had as to the specifics of the channel distortion. As discussed above, a hybrid delay-constrained ARQ and FEC for the BL are adopted to reduce the residual error, which works as follows. The sender determines the degree of protection for each transmission such that the expected end-to-end distortion is minimized while satisfying the QoS level requirement. Upon receiving the retransmission request for the corrupted packet, the source side will only transmit the necessary part of higher protection for the packet. Because only the protection code needs to be transmitted over the channel for retransmission, the transmission overhead can be reduced. In one implementation, an $RS(n, k)$ code is used for forward error correction, as mentioned before. Suppose n is fixed and let $t_i = \left\lfloor \frac{n - k_i}{2} \right\rfloor$ represent the protection level for the i^{th} transmission. Then, the protection rate needed for the BL delivery is calculated as follows:

$$R_{ARQ} = \sum_{i=1}^{bn} R_{prot}(t_i, R_{s_base}(i)) + \sum_{j=2}^{N_{max}-1} \left\{ \sum_{i=1}^{bn} [P_{fail}(i, j-1) \times R_{prot}(t_j, R_{s_base}(i))] \right\}, \quad (32)$$

$$R_{prot}(t, R_{ss}) = \frac{2t}{n} \times R_{ss}, \quad (33)$$

$$P_{fail}(i, j) = \prod_{l=1}^j P_{fail, packet}(i, l), \quad (34)$$

$$\text{and } P_{fail, packet}(i, j) = 1 - \sum_{x=0}^{t_j} \left\{ \sum_{y=0}^x \left[\binom{n}{y} p_s(i)^y (1 - p_s(i))^{n-y} \right] \right\}, \quad (35)$$

where bn is the number of source packets needed to be transmitted, $R_{prot}(t, R_{ss})$ is the bit rate needed for protecting R_{ss} at level t , $P_{fail}(i, j)$ is the probability of the i^{th} packet failed in the

past j times retransmission, $P_{fail,packet}(i, j)$ is the probability of the i^{th} packet that is failed in the j^{th} retransmission, and $p_s(i)$ is the probability of symbol failure of the i^{th} packet.

[0163] After hybrid FEC and delay-constrained ARQ protection for BL, only those blocks that cannot be recovered will cause the additional channel distortion. Thus, the channel

distortion of the BL can be described as $D(R_{ARQ}) = \sum_{i=0}^{bn} [P_{fail}(i, N_{max} - 1) \times D_c(i)]$, (36)

[0164] where $D_c(i)$ is the channel distortion caused by the loss of packet i .

[0165] Now an analysis is made of the channel distortion in ELs. Considering the

dependency among layers, UEP is applied for the ELs. Similar to the BL, use $t_i = \left\lfloor \frac{n - k_i}{2} \right\rfloor$ to

represent the protection level for the i^{th} layer. The protection rate needed for the ELs

delivery is then represented as follows: $R_{FEC} = \sum_{i=1}^L R_{prot}(t_i, R_{s_enh}(i))$, (37)

where L is the number of layers needed to be transmitted, and $R_{prot}(t, R_{ss})$ is the bit rate needed for protecting R_{ss} at level t , which had been defined in (33). Then, the channel distortion of ELs after UEP can be expressed as:

$$D(R_{FEC}) = \sum_{i=1}^L \left[\sum_{j=1}^{bn_i} (P_{fail,layer}(i, j) \times D_c(j)) \right], \quad (38)$$

$$P_{fail,layer}(i, j) = P_{fail,packet,layer}(i, j) \mid \prod_{m=1}^{i-1} (1 - P_{fail,packet,layer}(m, j)), \quad (39)$$

$$\text{and } P_{fail,packet,layer}(i, j) = 1 - \sum_{x=0}^{t_i} \left\{ \sum_{y=0}^x \left[\binom{n}{y} p_s(j)^y (1 - p_s(j))^{n-y} \right] \right\}, \quad (40)$$

where bn_i is the number of source packets needed to be transmitted in the i^{th} layer, $P_{fail,layer}(i, j)$ is the probability that the j^{th} packet in the i^{th} layer is corrupted while the corresponding packets in the previous layers are correct, and $P_{fail,packet,layer}(i, j)$ is the probability that the j^{th} packet is corrupted in the i^{th} layer.

[0166] Substituting Eqs. (32, 36, 37, 38) into Eq. (29), the distortion-minimized resource allocation for scalable video delivery can be solved given the total available bit rate budget $R(t)$ at time t .

[0167] Figure 20 depicts the corresponding rate-distortion relation of a hybrid UEP and delay-constrained ARQ scheme of one implementation. Based on the above analysis and from Figure 20, it can be seen that $D_{\min-ARQ} \leq D_{\min} \leq D_{\min-FEC}$. In the meantime, the delay bound of media (T_{bound}) is satisfied.

[0168] 8.3 Power-minimized Resource Allocation

[0169] Besides the channel bandwidth capacity, another highly limited resource in wireless networks is power, which includes the transmitter power and receiver power. In one implementation, consideration of the receiver power in the mobile devices is taken, which consists of receiving power, source decoding power and channel decoding power. It is observed that both the source and the channel have a tradeoff between the coding rate and the processing power consumption. Thus, the power-optimized resource allocation problem can be formulated as: given the fixed bandwidth capacity, how should the bits be allocated among the source, the FEC, and the ARQ so as to achieve the minimum power consumption under the desired end-to-end distortion range. Let $R(t)$ represent the available bit rate at time t , $R_S(t)$, $R_{ARQ}(t)$, and $R_{FEC}(t)$ represent the bit rate used for the source, the FEC, the ARQ at time t , respectively, and $D(t)$ represent the tolerable distortion at time t . Then, the power-minimized resource allocation can be described as:

$$\min_{\{R_s, R_{ARQ}, R_{FEC}\}} PC = PC_{rec,s}(R_s) + PC_{rec,ARQ}(R_{ARQ}) + PC_{rec,FEC}(R_{FEC}) \\ + PC_s(R_s) + PC_{ARQ}(R_{ARQ}) + PC_{FEC}(R_{FEC}) \text{ subject to}$$

$$D_s(R_s) + D_{ARQ}(R_{ARQ}) + D_{FEC}(R_{FEC}) \leq D(t) \text{ and } R_S(t) + R_{ARQ}(t) + R_{FEC}(t) \leq R(t), \quad (41)$$

where $PC_{rec,s}(R_s)$, $PC_{rec,ARQ}(R_{ARQ})$, and $PC_{rec,FEC}(R_{FEC})$ are the power consumed for receiving the source, the ARQ, and the FEC, respectively, and $PC_s(R_s)$, $PC_{ARQ}(R_{ARQ})$, $PC_{FEC}(R_{FEC})$ are consumed power for the source coding, the ARQ, and the FEC, respectively.

[0170] Source decoding and channel decoding have different power consumptions. For the source part, the receiving power is composed of receiving powers for both the BL and ELs.

$$\text{Mathematically, } PC_{rec,s}(R_s) = \sum_{i=1}^{bn} [\rho_{rec} \times (R_{s_base}(i))] + \sum_{j=1}^L \left\{ \sum_{i=1}^{bn_j} [\rho_{rec} \times (R_{s_enh}(i, j))] \right\}, \quad (42)$$

where bn_j is the number of blocks in the j^{th} layer, and ρ_{rec} is the power consumed for per bit transmission. The consumed processing power for the source part is related to the source decoding rate, which is denoted as

$$PC_s(R_s) = \rho_s(R_s) = \sum_{i=1}^{bn} \rho_s(R_{s_base}(i)) + \sum_{j=1}^L \left\{ \sum_{i=1}^{bn_j} \rho_s(R_{s_enh}(i, j)) \right\}, \quad (43)$$

where $\rho_s(\cdot)$ can be obtained from Figure 15.

[0171] As for the channel part, the consumed processing power is related to both the source decoding rate and the channel protection rate, which is represented as

$$PC_{FEC}(R_s, R_{FEC}) = \rho_c(R_s, R_{FEC}) = \rho_c(R_s, t), \text{ where } t \text{ is the error protection level, and } \rho_c(\cdot)$$

can be obtained from Figure 16.

[0172] In the hybrid delay-constrained ARQ and FEC scheme that used for the BL of one implementation, any corrupted packet is allowed to be transmitted, at the most, N_{\max} times.

Once receiving the retransmission request, a higher protection level is determined by the sender to achieve the desired video quality. On the sender side, only the code that has the higher protection will be transmitted to the receiver. While on the receiver side, different channel decoding would be performed after each transmission. Thus, the receiving power consumption for the BL is formulated as:

$$PC_{rec,ARQ}(R_{ARQ}) = \sum_{i=1}^{bn} [\rho_{rec} \times R_{prot}(t_1, R_{s_base}(i))] + \sum_{j=2}^{N_{max}-1} \sum_{i=1}^{bn} \{ [P_{fail}(i, j-1) \times \rho_{rec} \times R_{prot}(t_j, R_{s_base}(i))] \}, \quad (44)$$

where t_i is the error protection level for the i^{th} retransmission. Similarly, the processing power consumption for the BL is represented as

$$PC_{ARQ}(R_{ARQ}) = \sum_{i=1}^{bn} \rho_c(R_{s_base}(i), t_1) + \sum_{j=2}^{N_{max}-1} \sum_{i=1}^{bn} \{ [P_{fail}(i, j-1) \times \rho_c(R_{s_base}(i), t_j)] \}. \quad (45)$$

[0173] As discussed before, UEP is applied to ELs. To be specific, different channel protection bits will be transmitted for different layers on the sender side; while different channel decoding will be performed for different layers on the receiver side. The receiving power consumption for ELs is represented as:

$$PC_{rec,FEC}(R_{FEC}) = \sum_{j=1}^L \sum_{i=1}^{bn_j} \{ [\rho_{rec} \times R_{prot}(t_j, R_{s_enh}(i, j))] \}. \quad (46)$$

[0174] Similarly, the processing power consumption for ELs is expressed as

$$PC_{FEC}(R_{FEC}) = \sum_{j=1}^L \sum_{i=1}^{bn_j} \{ [\rho_c(R_{s_enh}(i, j), t_j)] \}. \quad (47)$$

[0175] Substituting Eqs. (42-47) into Eq. (41), the power-minimized resource allocation for scalable video delivery can be solved, given the total available bit rate budget $R(t)$ at time t and the desired distortion range $D(t)$ at time t . Note that optimization methods, such as Lagrange multiplier and penalty function methods, can be used to solve the constrained non-linear optimization problem.

[0176] 9. Simulation Results

[0177] The simulations in this Section 9 demonstrate the effectiveness of various implementations of the channel-adaptive resource allocation scheme. The purpose of this simulation is to show that:

[0178] (1) Implementations of the distortion-optimized resource allocation approach can achieve the minimal distortion for PFGS delivery using an implementation of an unequal error protection (UEP) and delay-constrained ARQ error control scheme.

[0179] (2) Implementations of the power-optimized resource allocation approach can achieve significant power saving ratio within a tolerable distortion range for PFGS using the hybrid UEP and delay constrained ARQ error control scheme.

[0180] 9.1 Simulation Environment

[0181] The performance of the resource allocation scheme is analyzed in a simulation environment with the parameters shown in Table 1. Two-path Rayleigh fading W-CDMA channel is used in the simulation to generate the error pattern. The Application Layer data is packetized and transported in UDP packet with the size of 576 bytes. The UDP packet is further segmented into several RLC frames with the frame size varies from 320 bits to 640 bits. The maximal number of retransmission times for a RLC frame is 3. The application available bit rate in the simulation varies from 256 Kbps to 1.5 Mbps, and the block error rate is divided into high error and low error cases.

[0182] Table1. Simulation Parameters

Channel	Two-path Rayleigh fading
Multipath profile	ITU Outdoor-to-indoor A
Mobile speed	3km/h
UDP packet size	576 Bytes
RLC-PDU (includes CRC)	320 bits, 640 bits
CRC bits	16
Maximal RLC retransmission	3

times	
TTI	10 ms, 20 ms, 40 ms, 80 ms
Channel coding	RS (245, 200), (225, 180) Convolutional coding: 1/3, 2/3
Pilot/TPC/TFI bits per slot	6/2/2
Channel estimation	Present slot and 7 previous slots interpolated
Simulation length	80s
BLER target	Low error case: $8e-4$ to $5e-3$ High error case: $5e-3$ to $2e-2$
Application available bit rate	256 Kbps to 1.5 Mbps

[0183] 9.2 Performance Of Distortion-Minimized Resource Allocation

In this simulation, tests were made of:

- (1) An implementation of the channel-adaptive distortion-optimized resource allocation scheme for hybrid UEP and delay-constrained ARQ;
- (2) PFGS with UEP, which used fixed channel protection for each priority (25% protection for base layer, 10% protection for enhance layer); and
- (3) PFGS with fixed channel protection in base layer (25% protection).

[0184] In all the cases, the first frame was intra-coded, and the remaining frames were inter-coded. The testing video sequence is in the MPEG-4 test sequence “*Foreman*”, that is coded in CIF at a temporal resolution of 10 fps. There were conducted simulations under the channel bandwidth varying from 256kbps to 1.5Mbps. To demonstrate the effectiveness of the implementations, the simulations were performed in both high error and low error cases. Note that in all these simulations the total rates including source and channel are the same for all the cases.

[0185] In this simulation, the channel rate is obtained by analyzing the application throughput; while the channel condition is obtained by the report from the Physical Layer. Given the channel rate and the channel condition, there was first added a strong protection

to the base layer so that the residual error probability in the BL is lower than 10^{-5} . Then the optimal FEC rate and the source rate were found, followed by adding error protection to each enhance layer. Note that in the simulation of the hybrid delay-constrained ARQ and UEP scheme, only one re-transmission in the Application Layer is performed.

[0186] Figures 21a and 21b show that Average Peak Signal To Noise Ratio (PSNR) for the MPEG-4 test sequence “Foreman” using the three tested schemes under different bit rates. These figures also show the measured average PSNR and distortion at different channel rates under high-error channels (Figure 21a) and low-error channels (Figure 21b). It can be seen that the implemented scheme achieves the best performance among different channel conditions and various channel rates. Notice that the higher channel rate, the larger difference between the implemented scheme and the other two fixed UEP schemes. It can also be seen that from Figures 14a-14b, the PSNR that is obtained using the other two schemes increases slower than the implemented scheme. This is because the target bits are allocated according to the quality impact of each layer in the implemented approach. It can be further observed that the PSNR increases as the channel rate increases. The speed of the increase slows down as the information added becomes less important.

[0187] Tables 2a and 2b shows simulation results for the MPEG-4 test sequence “Foreman” for high and low channel error, respectively. Tabular comparison results are seen in Tables 2a and 2b of the average PSNR for the whole sequence and average protection ratio used in the implemented channel-adaptive resource allocation scheme and the other two schemes. Note that the total available bandwidth is the same in all the cases.

[0188] Table 2a: Simulation results for the MPEG-4 test sequence “Foreman”: High error channel

Channel	Our Scheme		Fixed UEP		Fixed Base Protection	
Bandwidth (Kbps)	Average PSNR (dB)	Average Protection Ratio (%)	Average PSNR (dB)	Average Protection Ratio (%)	Average PSNR (dB)	Average Protection Ratio (%)
320	30.91	16.6	28.95	18.8	29.63	14.2
448	31.88	19.6	29.81	16.2	29.81	10.1
576	32.72	21.0	30.54	14.8	29.57	7.9
768	33.33	19.4	30.71	13.6	29.68	5.9
1024	34.06	19.2	30.97	12.7	30.02	4.4
1280	34.66	19.2	31.37	12.2	29.73	3.6
1536	35.07	26.1	31.51	11.9	29.92	3.0

[0189]

[0190] Table 2b Simulation results for the MPEG-4 test sequence “Foreman”: Low error channel

Channel	Implemented Scheme		Fixed UEP		Fixed Base Protection	
Bandwidth (Kbps)	Average PSNR (dB)	Average Protection Ratio (%)	Average PSNR (dB)	Average Protection Ratio (%)	Average PSNR (dB)	Average Protection Ratio (%)
256	30.71	7.6	30.04	20.8	29.99	17.7
320	31.34	8.2	30.71	18.8	30.50	14.2
448	32.47	11.6	31.93	16.2	31.24	10.1
576	33.44	12.4	32.87	14.8	31.57	7.9

768	34.57	12.9	33.83	13.6	31.85	5.9
1024	36.05	15.1	34.79	12.7	32.03	4.4
1280	37.07	16.5	35.16	12.2	31.92	3.6
1536	37.26	24.6	35.28	11.9	32.05	3.0

[0191] Figures 22a and 22b graphically presents PSNR comparison results for the MPEG-4 test sequence “Foreman” at 320kbps channel rate using the implemented approach and two fixed UEP schemes for high and low error cases, respectively. From the graphs seen in Figures 22a-22b, it can be seen that the video quality obtained using the implemented approach is higher than the ones with other two schemes. Meanwhile, the video quality changes more smoothly in the implemented scheme.

[0192] Figures 23a-f show comparisons of the reconstructed 44th video frame (Figures 23a-23c) and 50th video frame (23d-23f) of the MPEG-4 test sequence “Foreman”. The images on the left (23a, 23d) are reconstructed by the implemented resource allocation scheme, those in the middle (23b, 23e) are reconstructed using fixed protection only for the base layer, and those on the right (23c, 23f) are obtained by UEP scheme. Figures 23a-f show comparisons of the reconstructed frames using the implemented approach and the other two schemes. Therein, Figure 23a is the reconstructed 44th frame using the implemented resource allocation scheme, Figure 23b is the reconstructed 44th frame using fixed protection only for base layer, and Figure 23c shows the reconstructed 44th frame using fixed UEP scheme. Figure 23d is the reconstructed 50th frame using the implemented resource allocation scheme, Figure 23e is the reconstructed 50th frame using fixed protection only for base layer, and Figure 23f shows the reconstructed 50th frame using fixed UEP scheme.

[0193] From Figures 21a-23f and Table 2, it can be seen that the implemented channel-adaptive distortion-minimized resource allocation scheme obtains better results than the fixed UEP and fixed base-layer protection scheme under fading channel condition with different error rates, both subjectively and objectively.

[0194] 9.3 Performance Of Power-Minimized Resource Allocation

[0195] The simulation was to demonstrate the effectiveness of the implemented power-optimized resource allocation scheme for PFGS. In this simulation tests were made of:

[0196] (1) the implemented channel-adaptive power-minimized resource allocation scheme with hybrid UEP and delay-constrained ARQ;

[0197] (2) the implemented channel-adaptive distortion-minimized resource allocation scheme with hybrid UEP and delay-constrained ARQ;

[0198] (3) PFGS with UEP, which used fixed channel protection for each priority (25% protection for base layer, 10% protection for enhance layer). In the implemented power-minimized resource allocation case, various ranges of tolerable distortion are tested.

[0199] Again, the MPEG-4 test sequence “Foreman” was coded in CIF at a temporal resolution of 10 fps. The first frame was intra-coded and the remaining frames were inter-coded. Simulations were conducted under the channel bandwidth varying from 256kbps to 1Mbps. To demonstrate the effective of the implemented scheme, the simulations were performed in both high error and low error cases. Since the receiving power is relatively small comparing with the source and channel processing power as stated above, calculations were made of the source and channel processing power in the simulation.

Table 3. Comparison results for the MPEG-4 test sequence “*Foreman*” in the high error case

Schemes	256kbps				320kbps			
	PSNR (dB)	Quality Reduction Ratio (%)	Time (ms)	Power Saving Ratio (%)	PSNR (dB)	Quality Reduction Ratio (%)	Time (ms)	Power Saving Ratio (%)
1	29.59	0	164.11	0	30.26	0	172.88	0
2	28.13	4.92	160.07	2.47	28.44	6	165.90	4.04
3	29.47	0.43	157.41	4.08	30.06	0.67	167.66	3.02
4	29.33	0.91	155.35	5.33	29.91	1.17	165.41	4.32
5	29.09	1.72	145.51	11.33	29.56	2.33	161.49	6.59
6	28.88	2.42	132.32	19.37	29.32	3.12	152.28	11.91

[0200] Table 3 tabulates the comparison results of the average computational time (representing the power consumption) and the PSNR for the whole sequence for these three schemes in high error case. Scheme 1 of Table 3 uses the optimal resource allocation scheme without considering power consumption. It needs the longest computational time while achieving the highest PSNR. Scheme 1 of Table 3 was used as the comparison criteria. Scheme 2 uses the fixed UEP. As mentioned above, different a desired distortion tolerance range may have different impacts on video quality and power consumption. Schemes 3, 4, 5, 6 of Table 3 use the power-minimized resource allocation scheme with the desired distortion increment range 10%, 20%, 40%, 60%, respectively.

[0201] Figures 24a and 24b show comparison results for the MPEG-4 test sequence “Foreman” at 256kbps available bandwidth in the high error case. It can be seen from Figures 24a-24b that the implemented scheme requires less computational time than the other schemes almost in every frame. In the meanwhile, the PSNR obtained in the implemented scheme is a little less than the one in the optimal resource allocation scheme while it is higher than the one in the fixed UEP scheme. Note that those performances vary within the various tolerable distortion ranges. In Figures 25a and 25b, the desired distortion increment range is 60%.

[0202] Figures 25a and 25b show comparisons of the reconstructed frames using the implemented approach and the other two schemes at 256kbps in the high error case. Figure 18a is a video sequence that is the reconstructed 36th frame using the implemented power-minimized resource allocation scheme, Figure 18b is the reconstructed 36th frame using the implemented distortion-minimized resource allocation scheme, and Figure 18c shows the reconstructed 36th frame using fixed UEP scheme. It can be seen from Figures 18a-18cc that the image quality obtained by power-minimized resource allocation scheme is quite similar to the one obtained by distortion-minimized resource allocation scheme, but better than the one obtained by the fixed UEP scheme.

[0203] Table 4 tabulates comparison results of average computational time and PSNR for the whole sequence in these three schemes of Figures 25a-25c in low error case. Schemes 1-6 are the same as in the high error case.

[0204] Table 4. Comparison results for the MPEG-4 test sequence “Foreman” in the low-error case

Schemes	256kbps				320kbps			
	PSNR (dB)	Quality Reduction Ratio (%)	Time (ms)	Power Saving Ratio (%)	PSNR (dB)	Quality Reduction Ratio (%)	Time (ms)	Power Saving Ratio (%)
1	30.06	0	159.39	0	30.79	0	166.69	0
2	29.32	2.47	158.79	0.38	29.69	3.55	165.66	0.62
3	29.95	0.39	156.48	1.83	30.72	0.23	164.83	1.12
4	29.83	0.8	154.66	3.0	30.65	0.44	161.14	3.33
5	29.69	1.24	148.40	6.90	30.43	1.17	159.70	4.19
6	29.18	2.95	139.07	12.75	29.96	2.69	153.38	7.99

[0205] Figures 26a and 26b show the comparison results for the MPEG-4 test sequence

“Foreman” at 320kbps available bandwidth in the low-error case. It can be seen that the implemented scheme requires less computational time than the other schemes almost in every frame. In the meantime, the PSNR obtained in the implemented scheme is a little less than the one in the optimal resource allocation scheme but higher than the one in the fixed UEP scheme. Note that those performances vary within the various tolerable distortion ranges. In Figures 26a and 26b, the desired distortion increment range is 60%.

[0206] Figures 27a-27c show comparisons of the reconstructed frames using the implemented approach and the other two schemes at 320kbps in the low error case. Figure 27a is the reconstructed 42nd frame using the implemented power-minimized resource allocation scheme, Figure 27b is the reconstructed 42nd frame using the implemented

distortion-minimized resource allocation scheme, and Figure 27c shows the reconstructed 42nd frame using fixed UEP scheme. It can be seen from Figures 27a-c that the image quality obtained by the implemented power-minimized resource allocation scheme is quite similar to that obtained by the implemented distortion-minimized resource allocation scheme, but better than the one obtained by the fixed UEP scheme.

[0207] From Figures 24a-27c and Tables 3-4, it can be seen that the implemented channel-adaptive power-minimized resource allocation scheme obtains better results than the fixed UEP scheme in different error cases, both subjectively and objectively. As such, the implemented scheme can achieve significant power saving ratio within a tolerable distortion range.

[0208] In summary, the simulation results presented in this Section 9 show that:

- (1) The implemented distortion-minimized resource allocation scheme with hybrid UEP and delay-constrained ARQ can achieve the minimal distortion for PFGS; and
- (2) The implemented power-minimized resource allocation with hybrid UEP and delay-constrained ARQ can achieve significant power saving ratio within a tolerable distortion range.

[0209] The inventors intend these exemplary implementations to be examples and not to limit the scope of the present invention. Rather, the inventors have contemplated that the present invention might also be embodied and implemented in other ways, in conjunction with other present or future technologies

[0210] 10. Exemplary Computing System and Environment

Figure 8 illustrates an example of a suitable computing environment 800 within which the Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA, as described herein, may be implemented (either fully or partially). The computing

environment 800 may be utilized in the computer and network architectures described herein.

[0211] The exemplary computing environment 800 is only one example of a computing environment and is not intended to suggest any limitation as to the scope of use or functionality of the computer and network architectures. Neither should the computing environment 800 be interpreted as having any dependency or requirement relating to any one or combination of components illustrated in the exemplary computing environment 800.

[0212] Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may be implemented with numerous other general purpose or special purpose computing system environments or configurations. Examples of well known computing systems, environments, and/or configurations that may be suitable for use include, but are not limited to, personal computers, server computers, thin clients, thick clients, hand-held or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

[0213] Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may be described in the general context of computer-executable instructions, such as program modules, being executed by a computer. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program

modules may be located in both local and remote computer storage media including memory storage devices.

[0214] The computing environment 800 includes a general-purpose computing device in the form of a computer 802. The components of computer 802 can include, by are not limited to, one or more processors or processing units 804, a system memory 806, and a system bus 808 that couples various system components including the processor 804 to the system memory 806.

[0215] The system bus 908 represents one or more of any of several types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port, and a processor or local bus using any of a variety of bus architectures. By way of example, such architectures can include an Industry Standard Architecture (ISA) bus, a Micro Channel Architecture (MCA) bus, an Enhanced ISA (EISA) bus, a Video Electronics Standards Association (VESA) local bus, and a Peripheral Component Interconnects (PCI) bus also known as a Mezzanine bus.

[0216] Computer 802 typically includes a variety of computer readable media. Such media can be any available media that is accessible by computer 802 and includes both volatile and non-volatile media, removable and non-removable media.

[0217] The system memory 806 includes computer readable media in the form of volatile memory, such as random access memory (RAM) 810, and/or non-volatile memory, such as read only memory (ROM) 812. A basic input/output system (BIOS) 814, containing the basic routines that help to transfer information between elements within computer 802, such as during start-up, is stored in ROM 812. RAM 810 typically contains data and/or program modules that are immediately accessible to and/or presently operated on by the processing unit 804. System memory 806 is an example of a means for storing data having inputs and

outputs and a frame buffer for storing pixel representations from which to render a three-dimensional graphical object.

[0218] Computer 802 may also include other removable/non-removable, volatile/non-volatile computer storage media. By way of example, Figure 8 illustrates a hard disk drive 816 for reading from and writing to a non-removable, non-volatile magnetic media (not shown), a magnetic disk drive 818 for reading from and writing to a removable, non-volatile magnetic disk 820 (e.g., a “floppy disk”), and an optical disk drive 822 for reading from and/or writing to a removable, non-volatile optical disk 824 such as a CD-ROM, DVD-ROM, or other optical media. The hard disk drive 816, magnetic disk drive 818, and optical disk drive 822 are each connected to the system bus 808 by one or more data media interfaces 826. Alternatively, the hard disk drive 816, magnetic disk drive 818, and optical disk drive 822 can be connected to the system bus 808 by one or more interfaces (not shown).

[0219] The disk drives and their associated computer-readable media provide non-volatile storage of computer readable instructions, data structures, program modules, and other data for computer 802. Although the example illustrates a hard disk 816, a removable magnetic disk 820, and a removable optical disk 824, it is to be appreciated that other types of computer readable media which can store data that is accessible by a computer, such as magnetic cassettes or other magnetic storage devices, flash memory cards, CD-ROM, digital versatile disks (DVD) or other optical storage, random access memories (RAM), read only memories (ROM), electrically erasable programmable read-only memory (EEPROM), and the like, can also be utilized to implement the exemplary computing system and environment.

[0220] Any number of program modules can be stored on the hard disk 816, magnetic disk 820, optical disk 824, ROM 812, and/or RAM 810, including by way of example, an operating system 826, one or more graphics application programs 828, other program modules 830, and program data 832. Each of such operating system 826, one or more graphics application programs 828, other program modules 830, and program data 832 (or some combination thereof) may include an embodiment of program code to perform Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA.

[0221] A user can enter commands and information into computer 802 via input devices such as a keyboard 834 and a pointing device 836 (e.g., a “mouse”). Other input devices 838 (not shown specifically) may include a microphone, joystick, game pad, satellite dish, serial port, scanner, and/or the like. These and other input devices are connected to the processing unit 804 via input/output interfaces 840 that are coupled to the system bus 808, but may be connected by other interface and bus structures, such as a parallel port, game port, or a universal serial bus (USB).

[0222] A monitor 842 or other type of display device can also be connected to the system bus 808 via an interface, such as a video adapter/accelerator 844. Video adapter/accelerator 844 is intended to have a component thereof that represents 3-D commodity graphics hardware. As such, the 3-D commodity graphics hardware is coupled to the high-speed system bus 806. The 3-D commodity graphics hardware may be coupled to the system bus 808 by, for example, a cross bar switch or other bus connectivity logic. It is assumed that various other peripheral devices, or other buses, may be connected to the high-speed system bus 808, as is well known in the art. Further, the 3-D commodity graphics hardware may be coupled through one or more other buses to system bus 808.

[0223] In addition to the monitor 842, other output peripheral devices can include components such as speakers (not shown) and a printer 846 which can be connected to computer 802 via the input/output interfaces 840.

[0224] Computer 802 can operate in a networked environment using logical connections to one or more remote computers, such as a remote computing device 848. By way of example, the remote computing device 848 can be a personal computer, portable computer, a server, a router, a network computer, a peer device or other common network node, and the like.

[0225] The remote computing device 848 is illustrated as a portable computer that can include many or all of the elements and features described herein relative to computer 802. Logical connections between computer 802 and the remote computer 848 are depicted as a local area network (LAN) 850 and a general wide area network (WAN) 852. Such networking environments are commonplace in offices, enterprise-wide computer networks, intranets, and the Internet.

[0226] When implemented in a LAN networking environment, the computer 802 is connected to a local network 850 via a network interface or adapter 854. When implemented in a WAN networking environment, the computer 802 typically includes a modem 856 or other means for establishing communications over the wide network 852. The modem 856, which can be internal or external to computer 802, can be connected to the system bus 808 via the input/output interfaces 840 or other appropriate mechanisms. It is to be appreciated that the illustrated network connections are exemplary and that other means of establishing communication link(s) between the computers 802 and 848 can be employed.

[0227] In a networked environment, such as that illustrated with computing environment 800, program modules depicted relative to the computer 802, or portions thereof, may be

stored in a remote memory storage device. By way of example, remote application programs 858 reside on a memory device of remote computer 848. For purposes of illustration, application programs and other executable program components such as the operating system are illustrated herein as discrete blocks, although it is recognized that such programs and components reside at various times in different storage components of the computing device 802, and are executed by the data processor(s) of the computer.

[0228] Computer-Executable Instructions

An implementation of Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may be described in the general context of computer-executable instructions, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Typically, the functionality of the program modules may be combined or distributed as desired in various embodiments.

[0229] Exemplary Operating Environment

Figure 8 illustrates an example of a suitable operating environment 800 in which an exemplary Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may be implemented. Specifically, the exemplary Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA described herein may be implemented (wholly or in part) by any program modules 828-830 and/or operating system 826 in Figure 8 or a portion thereof.

[0230] The operating environment is only an example of a suitable operating environment and is not intended to suggest any limitation as to the scope or use of functionality of the exemplary Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-

CDMA described herein. Other well known computing systems, environments, and/or configurations that are suitable for use include, but are not limited to, personal computers (PCs), server computers, hand-held or laptop devices, multiprocessor systems, microprocessor-based systems, programmable consumer electronics, wireless phones and equipments, general- and special-purpose appliances, application-specific integrated circuits (ASICs), network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

[0231] Computer Readable Media

An implementation of an exemplary Channel and QoS Level Adaptive Scheme for Multimedia Delivery over W-CDMA may be stored on or transmitted across some form of computer readable media. Computer readable media can be any available media that can be accessed by a computer. By way of example, and not limitation, computer readable media may comprise “computer storage media” and “communications media.”

[0232] “Computer storage media” include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules, or other data.

Computer storage media includes, but is not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by a computer.

[0233] “Communication media” typically embodies computer readable instructions, data structures, program modules, or other data in a modulated data signal, such as carrier wave

or other transport mechanism. Communication media also includes any information delivery media.

[0234] The term “modulated data signal” means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, RF, infrared, and other wireless media. Combinations of any of the above are also included within the scope of computer readable media.

[0235] For purposes of the explanation, specific numbers, materials and configurations are set forth above in order to provide a thorough understanding of the present invention.

However, it will be apparent to one skilled in the art that the present invention may be practiced without the specific exemplary details. In other instances, well-known features are omitted or simplified to clarify the description of the exemplary implementations of present invention, and thereby better explain the present invention. Furthermore, for ease of understanding, certain method operations are delineated as separate operations; however, these separately delineated operations should not be construed as necessarily order dependent in their performance.

[0236] The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

Appendix

[0237] Figure 21a: Peak Signal To Noise Ratio (PSNR) vs.

[0238] Channel Rate (kbps):	320	448	576	768	1024	1280	1536
[0239] Implement scheme:	30.91	31.88	32.72	33.33	34.06	34.66	35.07
[0240] Fixed UEP:	28.95	29.81	30.54	30.71	30.97	31.37	31.51
[0241] Fixed base protection:	29.63	29.81	29.57	29.68	30.02	29.73	29.92
[0242]							

[0243] Figure 21b: Peak Signal To Noise Ratio (PSNR) vs.

Channel Rate (kbps):	256	320	448	576	768	1024	1280	1536
[0244] Implement scheme:	30.71	31.34	32.47	33.44	34.57	36.05	37.07	37.26
[0245] Fixed UEP:	30.04	30.71	31.93	32.87	33.83	34.79	35.156	35.28
[0246] Fixed base protection:	29.99	30.5	31.24	31.57	31.85	32.03	31.92	32.05
[0247]								

[0248] Figure 22a: Peak Signal To Noise Ratio (PSNR) for 100 Frames

[0249]

[0250] Implementation scheme with ARQ

[0251]	34.584064	34.815634	34.344908	34.100972	33.758754
	32.978592	32.890178	33.20582	33.298668	33.167785
	32.412051	32.518231	32.439534	32.278182	32.648309
	32.616226	32.502125	32.134657	32.09542	31.977119
	31.15211	31.467163	32.25547	32.233202	32.569298
	32.52232	32.368633	31.856035	31.413679	31.333274
	31.893364	32.102961	31.621019	31.800835	31.996096
	32.181731	32.530733	32.637176	33.076393	33.289795
	33.208431	33.230925	32.451307	32.113184	32.281769
	32.078777	32.036618	31.836756	32.181525	32.280067
	32.406393	32.714067	32.047437	30.786783	30.590401
	30.741063	31.962628	31.281068	30.672066	30.524995
	31.944598	32.062382	32.566246	32.724144	32.317652
	31.462232	32.339913	32.733208	32.581152	32.457355
	29.734556	29.266855	28.637988	27.729666	27.85359
	28.481684	28.201797	27.009832	27.170984	27.229765
	26.892364	26.694874	26.50844	26.326214	26.462474
	26.498556	26.699264	26.692219	26.741758	26.640257
	26.883102	27.039486	27.10895	27.190464	27.167556
	27.514204	28.155396	28.611868	29.707674	30.321413

[0252]

[0253] Fixed UEP

[0254]	33.555906	33.273229	32.570944	32.138	31.998353
	31.362105	31.061719	31.208006	31.291784	31.031312
	31.348725	31.774103	31.660492	31.621137	31.670136
	31.85806	31.735288	31.460515	30.893641	31.030859
	31.102195	31.539451	31.667298	31.609895	31.56764
	31.537493	31.16093	30.467715	29.960103	29.78623
	30.387632	30.498289	30.181181	30.415074	30.102668
	30.160028	30.486056	31.035339	31.560521	31.70428

31.792452	31.680501	31.25544	30.420998	30.035175
30.791577	30.947541	30.739382	30.958631	31.009252
31.010833	30.132885	28.282037	28.332695	28.695135
28.804267	29.299764	29.603377	28.801373	28.686934
29.284962	29.284057	29.141708	29.544352	29.259647
28.633205	29.252366	30.116935	29.999031	29.682484
28.730133	28.396302	27.804316	26.805856	26.502193
27.289533	27.130036	26.155077	26.29087	26.409276
26.183439	26.039674	26.029993	25.937897	25.962496
26.061668	26.038562	26.140811	26.141756	26.191488
24.553248	24.399607	24.348149	24.591621	24.468334
24.083734	24.151303	24.603374	24.302976	24.385349

[0255]

[0256] Fixed base layer protection

[0257]	33.344119	33.545962	32.782506	32.69721	32.489516
	31.474603	31.33189	31.419603	31.538126	31.47558
	31.440749	31.856797	31.623448	31.719015	31.699093
	31.819789	31.965195	31.599255	31.106089	31.225893
	31.594431	31.824474	32.0945	32.051565	31.938442
	31.925364	31.913838	31.217097	30.420276	28.723341
	28.738587	29.213046	29.46496	29.396602	29.423469
	29.817092	30.106455	30.525032	30.938684	31.06587
	31.081859	31.256357	31.123227	30.66014	30.425109
	30.165031	30.050734	30.028231	30.237586	30.468449
	30.535156	30.913904	29.991573	29.151249	29.594137
	29.727547	29.750637	29.247924	29.351956	29.441211
	28.938828	28.892434	29.849947	29.492811	29.595562
	29.194191	29.734474	30.770862	30.760421	30.470054
	28.697145	28.385275	28.09072	27.046915	26.722332
	27.425918	27.158195	26.128872	26.301383	26.419655
	26.492703	26.29796	26.199817	26.082412	26.068077
	26.190762	26.394935	26.469158	26.293702	26.284625
	26.127278	26.310634	27.545276	27.437447	26.981643
	27.424395	27.951454	28.126335	28.990652	29.541242

[0258]

[0259] **Figure 22b: Peak Signal To Noise Ratio (PSNR) for 100 Frames**

[0260]

[0261] Implementation scheme with ARQ

[0262]	34.94738	35.118324	34.675696	34.499966	33.96359
	33.57903	33.23996	33.655929	33.726705	33.621245
	33.093479	32.392199	32.911398	32.963432	33.005142
	33.155236	33.298492	32.86871	32.3511	32.499024
	32.588178	32.803967	32.884544	32.961091	32.867528
	32.972367	32.878631	32.311203	32.00821	31.95067
	32.134544	32.366693	32.013637	32.034769	32.074622
	32.415137	32.682418	32.786939	33.442895	33.585781
	34.119991	33.93889	33.571384	32.808901	33.161422

32.939919	33.190275	32.703196	32.594894	32.86225
33.107466	33.286899	32.47043	31.383163	31.916692
32.059049	32.283232	32.011069	31.581078	31.260409
32.503928	32.701151	32.491308	32.834499	32.62734
31.708479	32.72365	33.04559	33.21816	32.680315
30.071966	29.75507	29.206991	28.194102	27.903236
28.707771	28.095846	27.04945	27.595877	27.705015
26.943955	26.710923	26.561441	26.39105	26.599079
26.685031	26.734076	26.814223	26.644283	26.636092
27.492871	27.619797	27.848451	27.819675	27.731827
28.040614	28.16432	28.649148	29.739188	30.345168

[0263]

[0264] Fixed UEP

[0265] 33.863438	34.19123	33.947459	33.732277	33.607062
33.044902	33.122538	33.493217	31.379998	31.678521
32.363539	32.551302	32.694083	32.624157	32.717486
32.847482	32.642646	32.373084	32.188786	32.137878
32.507368	32.340494	32.416993	32.387634	32.773815
32.780278	32.526604	31.931172	31.502642	31.365607
31.893116	31.94363	30.321111	30.871087	32.045844
32.110872	32.54428	32.705712	33.150052	33.124404
33.286775	33.027588	33.038225	32.0603132	32.350766
31.815435	32.369133	31.59256	30.28508	30.903158
31.201425	31.628095	31.568158	30.709361	29.540406
29.915918	31.128693	30.543815	29.64829	29.250653
30.910278	31.5912	31.829503	31.937259	32.056242
31.098834	31.822028	30.476655	32.143741	32.111077
29.598381	29.246677	28.697059	27.697511	27.664699
28.384527	27.692169	26.70693	27.247538	27.336703
26.756743	26.485184	26.361196	26.185787	26.436549
26.479201	26.540426	26.609321	26.627437	26.585036
27.159435	27.144852	27.384315	27.414968	27.291819
27.615905	28.423048	28.8222	29.570588	30.163609

[0266]

[0267] Fixed base layer protection

[0268] 33.841561	34.029631	33.722456	33.561577	33.719744
33.10316	33.165899	33.414431	32.944044	32.048277
31.369715	31.952138	32.51588	32.337277	32.314219
32.461397	31.871278	31.87605	32.134708	31.975074
31.892246	32.031635	31.9697	32.023494	32.047622
32.185298	32.305404	31.333946	31.033338	30.859751
31.630567	31.635496	31.073448	31.317212	32.007921
31.918262	31.879376	32.303759	32.833565	32.826792
33.20918	33.15297	33.045643	32.0644311	32.304806
31.367739	32.305709	31.718316	30.343813	31.028059
30.707037	31.119546	31.028964	29.840198	30.240703
30.267253	30.225992	29.941022	29.278866	29.209585

30.314278	30.956111	30.954478	31.82286	32.201106
29.287882	30.729095	30.222262	31.703495	31.435439
29.547973	29.259899	28.506516	27.542414	27.640978
28.390176	27.945866	26.933452	27.214612	27.2862
26.575424	26.386778	26.221845	26.108971	26.414219
26.366848	26.316556	26.436079	26.464688	26.478396
26.808717	26.926549	27.221917	27.283201	27.2789
27.708813	28.29302	28.679896	29.339364	30.038188

[0269] Figure 24a: ms for One Hundred (100) frames

[0270]

[0271] Distortion-minimized bit allocation

[0272]

131.849747	111.328445	103.72612	104.190979	105.060471
133.66394	185.130112	168.022125	188.113617	168.324051
150.906586	160.983994	161.196396	175.173172	167.871323
159.964935	180.41362	159.796478	172.228424	167.264648
160.143112	163.432236	177.003845	164.248947	166.93631
175.445648	177.176865	170.082352	176.064896	182.974503
170.532806	159.376236	158.871246	155.15686	153.375061
157.951065	146.529572	155.753647	151.434982	159.016937
154.127914	160.88855	163.211365	161.679993	169.005096
165.231766	167.196075	166.467056	168.298828	166.440964
161.691772	189.245255	190.520157	191.976624	183.451157
179.553879	181.720657	186.563187	185.602585	186.409256
197.227997	195.439423	202.271301	198.792938	203.498352
200.270172	193.379837	192.804077	195.474243	203.270584
172.76973	175.244339	174.739822	179.199219	158.995682
176.445389	167.352753	175.675949	165.922607	163.846085
157.834198	161.126465	157.059738	145.918198	143.912918
147.242355	161.144913	147.667709	143.07106	144.551239
154.474564	149.849365	147.369781	147.10347	148.962585
153.398453	149.917023	113.805908	117.348	110.676155

[0273]

[0274] Fixed UEP scheme

[0275]

117.748024	101.240181	94.827057	96.803688	95.117645
126.779793	176.270111	166.02832	178.424362	168.257721
146.921646	161.360474	155.819733	171.474594	167.673599
156.420868	182.460083	160.158096	170.235107	163.27623
152.676468	160.873566	173.394745	159.095261	159.543289
172.52478	174.609726	163.225021	174.83992	176.560318
170.142197	156.324707	156.834427	154.563217	150.865799
156.46785	143.65712	153.320236	148.456818	157.016235
148.817932	158.81427	157.347946	166.749023	168.632782
160.734451	163.271378	161.117172	166.887527	161.894592
154.771271	183.065567	185.197693	185.322113	177.744934
174.772232	177.19223	181.065338	178.893646	181.108444
190.587601	192.400208	194.327194	194.248077	195.640182

194.627914	187.62886	190.430267	190.084	195.407013
184.007111	176.642242	182.562698	177.412598	163.297562
175.681183	166.36824	174.372467	165.019531	159.246063
154.089798	157.996918	151.793625	143.855682	142.898926
146.263214	155.886063	146.601929	142.712463	150.805313
147.396057	142.165771	142.260712	140.985153	136.907974
149.883057	135.702591	100.354614	102.918327	99.574036

[0276]

[0277] Power-minimized bit allocation

[0278]

120.041176	102.794586	95.328941	96.011925	41.845097
127.769676	151.774384	166.294098	101.678429	167.111771
146.904709	157.308701	158.077408	161.163406	99.223534
115.100655	104.970589	156.685486	79.723534	101.303925
156.049179	157.800919	105.856865	160.350006	163.235535
161.827057	109.625885	159.630981	87.625885	108.728233
100.733727	119.020706	151.638718	151.416519	150.782516
152.567764	142.932205	150.866379	148.207108	154.337173
150.105927	158.87294	159.510529	160.385406	99.484627
160.61142	164.41011	162.444473	95.817963	162.054031
155.887482	182.82988	108.958824	108.545097	98.723534
174.26564	100.390198	90.211761	110.958824	107.545097
187.841568	188.639313	191.948318	191.03595	193.435211
192.072266	184.36348	187.081177	189.372528	192.482986
156.27066	162.933258	105.148003	101.346664	136.503113
164.49968	86.711998	98.910667	95.776001	158.558304
101.53624	103.03624	101.587769	94.805962	98.305962
136.59642	99.587769	95.246376	95.246376	122.152313
105.083687	113.063896	104.381256	110.02813	85.472572
113.508339	112.286118	105.619453	106.619453	106.620209

[0279]

[0280] Figure 24b: Peak Signal To Noise Ratio (PSNR) for 100 frames

[0281]

[0282] Distortion-minimized bit allocation

[0283]

32.322498	32.501194	31.99641	31.444376	31.549109
31.235359	31.224928	31.392536	31.130945	31.082987
30.535301	30.623419	30.459816	30.24991	29.938574
30.20599	30.48436	30.35689	29.640718	29.760805
30.458597	30.494816	30.094488	30.139265	30.826382
30.672396	30.366877	29.452442	29.494978	29.312765
29.804649	30.193666	30.288273	30.440762	30.547306
30.665632	30.823895	30.834284	30.924541	30.827398
30.903	30.889853	30.262161	30.10454	29.945143
29.691854	29.674223	30.021448	30.066031	30.026094
30.32147	31.029566	30.589905	30.491188	29.832798
30.490969	30.040779	30.331278	30.174158	29.790878
29.510172	31.536011	32.048958	32.759281	32.665855
32.386108	31.700802	32.524189	31.993883	32.542107

32.189812	29.50038	28.633879	27.476646	27.622562
28.301992	28.191521	27.031178	26.956877	27.061947
26.600945	26.358761	26.339312	26.263721	26.36833
26.453655	26.402941	26.524736	26.556416	26.538198
26.240713	26.299776	26.295441	26.355114	26.367025
26.369577	26.414268	26.337221	26.287823	26.323017

[0284] Fixed UEP scheme

[0285]

32.76445	32.523918	31.957508	31.69265	31.380962
30.878456	30.665537	30.840019	30.553745	30.525505
30.851795	30.845293	30.301865	30.009218	30.050762
25.647257	25.934521	25.666422	25.273829	25.461908
25.914541	25.953806	25.502752	26.070547	27.068813
27.100128	26.417849	25.634253	25.163382	25.005817
25.393442	26.119801	26.881056	27.15634	27.511539
27.512348	27.683977	27.693834	27.73941	27.698158
27.731428	27.650417	27.661751	27.517097	27.189459
27.375214	28.052849	28.24213	28.774414	29.264584
29.111176	29.439959	29.763861	29.08411	29.572641
29.27726	29.946745	29.773651	28.974758	28.532419
29.811853	30.389496	31.136351	31.29467	31.503204
30.88888	29.862869	30.943769	32.024578	31.192604
29.865419	28.86804	28.522495	27.402073	26.610247
27.42004	27.317692	26.429932	26.967823	27.132374
26.579254	26.404673	26.176584	26.121447	26.464489
26.466507	26.481096	26.572985	26.922665	26.87319
26.297012	26.42091	26.325377	26.482477	26.671587
26.787886	26.923321	26.726425	26.322226	26.399717

[0286] Power-minimized bit allocation

[0287]

31.402662	31.744953	31.904509	31.387861	30.037125
30.23288	29.616755	30.048956	29.496601	29.725777
30.339693	30.459587	30.335867	29.960716	29.580202
29.643839	29.598475	29.470827	28.896063	29.123291
30.197947	30.120117	29.462852	29.488787	30.491821
30.250776	29.383476	28.926773	28.532728	28.377432
29.05191	29.233852	29.204374	29.470682	30.1011
30.4655	30.467684	30.408428	30.341019	30.193151
30.75388	30.523832	29.985228	29.556038	28.497465
28.575802	29.805264	29.742201	29.105141	29.446571
30.3085	30.12188	28.950178	28.194868	28.723701
28.880905	29.253244	29.082638	28.547318	28.593328
30.388718	30.492994	30.500013	30.504562	30.51973
29.881721	30.863382	31.334511	32.259377	31.389193
29.092052	28.543377	27.858772	26.817146	26.651611
27.370985	27.100832	26.124441	26.292469	26.550947
26.205462	26.046564	26.018761	25.924183	26.015373

26.078547	26.002785	26.096176	26.137054	26.177452
26.090977	26.183649	26.169952	26.278873	26.215744
26.260914	26.300243	26.246401	26.175695	26.229383

[0288] Figure 26a: ms for One Hundred (100) frames

[0289]

[0290] Distortion-minimized bit allocation

[0291]

118.930351	104.626167	98.207764	99.653801	99.853882
129.881439	181.564941	179.866348	188.170425	182.40564
153.493851	166.78894	163.560181	174.819687	176.815994
166.450592	190.555527	166.068649	174.536942	167.165146
159.565491	171.199844	179.716003	169.075562	164.079117
176.759216	176.91153	167.240234	181.533463	177.269333
178.138596	163.787979	165.687759	162.280624	157.757172
163.82016	150.011978	162.786041	154.450348	165.510117
160.976242	173.970581	175.476242	185.780869	184.2742
175.389435	179.842346	181.093887	180.310349	180.227295
165.204971	183.866776	186.624908	187.661652	180.153183
180.642822	180.322357	181.625626	183.431213	182.114792
200.105026	200.174042	197.803421	200.365143	199.635239
201.132156	196.814011	195.624161	196.722198	198.029434
180.497879	182.843109	184.265457	185.415604	168.887527
180.0457	178.362137	179.874329	177.767059	166.90416
157.540787	165.346558	157.366714	151.401886	142.640335
154.841888	158.547638	154.139297	142.713882	151.423523
152.111679	149.125885	148.611603	150.003052	141.547607
150.836227	137.550201	102.973412	105.74086	103.841415

[0292]

[0293] Fixed UEP scheme

[0294]

120.038773	105.033936	99.10965	101.4851	100.26165
130.529434	181.848236	174.481644	187.012787	177.817413
151.570099	167.241333	161.105545	175.91687	173.573654
166.760544	187.414352	166.326828	170.901642	168.867264
159.327057	171.310898	179.515762	170.084778	164.464157
178.297806	178.388	168.766281	180.960052	179.358978
178.516235	163.2995	163.193359	163.544159	155.115784
164.345963	148.252213	163.800156	152.727997	166.061172
153.695007	170.552002	162.466019	184.948318	175.020477
170.43689	166.706726	172.968475	171.667999	175.353653
165.453705	187.259033	189.66449	189.60376	183.019531
180.216232	182.405884	184.201416	184.950348	185.432968
201.08667	199.012894	200.081543	201.63739	201.928421
202.632385	194.340363	194.248627	196.300308	200.692032
177.854935	182.121231	183.928986	182.920074	166.252472
177.748291	177.882645	177.083496	178.247086	161.408157
158.101013	165.239578	157.309784	151.235764	142.739868
150.758591	159.492599	149.65976	142.553406	148.173172

151.545563	148.880936	148.293015	149.171524	138.534195
149.723999	136.612076	102.853172	104.524864	100.348

[0295]

[0296] Power-minimized bit allocation

[0297]	116.160286	101.367767	93.349174	98.509254	94.083061
	127.265778	176.326828	173.531845	183.971161	175.295319
	150.525024	165.546906	157.238907	172.560684	92.417885
	165.219055	156.580338	164.53717	169.463501	165.123871
	153.292892	170.545807	164.954193	166.065308	160.114044
	174.264709	166.454193	163.20079	169.719788	173.021805
	96.208313	159.986038	161.038956	161.131378	153.236755
	162.937332	146.748856	161.281418	151.221649	164.089172
	158.211502	172.385483	172.080658	178.280243	184.2742
	175.389435	179.842346	180.593643	180.310349	179.894745
	159.006744	180.183655	182.677811	182.20047	175.528946
	174.163773	174.756241	177.868134	176.981644	178.95874
	191.976868	189.500946	190.34021	195.204285	192.825989
	193.121719	185.227036	187.408005	188.782532	192.075836
	180.497879	182.843109	168.184311	185.415604	165.006012
	176.878067	88.376472	101.543137	98.223534	162.607895
	94.190353	95.690353	95.690353	149.37262	113.746826
	148.79422	92.979057	149.748444	111.757751	147.531418
	92.24157	145.872864	93.373726	145.897263	86.16497
	149.361755	110.011765	102.973412	90.74157	103.841415

[0298]

[0299] Figure 26b: Peak Signal To Noise Ratio (PSNR) for 100 frames

[0300]

[0301] Distortion-minimized bit allocation

[0302]	33.388496	33.669373	33.408531	32.799397	30.139427
	30.941174	32.426456	32.854927	32.571697	32.68198
	31.899536	31.846209	31.576071	31.464401	31.454554
	31.535664	31.70369	31.374393	30.884878	30.991081
	31.84322	31.880999	31.921902	32.077953	32.249691
	32.09103	31.813311	31.417206	31.195223	30.951176
	31.131912	31.452793	31.354382	31.431969	31.562994
	31.665276	31.792545	31.696613	31.424019	31.365341
	31.680153	31.693405	31.484962	30.847776	30.457577
	30.488951	30.908718	31.033331	31.145531	31.553469
	32.505489	32.552998	32.18475	31.598314	31.842375
	32.081184	32.522167	32.311394	31.894968	31.953745
	33.654095	34.007706	34.440655	34.444752	34.279358
	33.444977	34.090092	34.420246	33.759293	33.987419
	30.601955	30.137341	29.726669	28.573614	28.805723
	29.522821	29.12192	27.954824	28.424179	28.454006
	27.151115	26.970095	26.884071	26.772938	26.701632
	26.747147	26.967503	27.014086	27.096952	27.067467

26.783464	26.673557	26.700537	26.783239	26.819414
26.880978	27.034023	26.982676	26.824421	26.851055

[0303]

[0304] Fixed UEP scheme

[0305]	33.231937	33.488609	33.362411	32.512974	32.163654
	32.023617	32.087288	32.531898	32.47287	32.210781
	31.624842	31.777941	31.66457	31.619427	31.418858
	31.532249	31.323067	31.165733	29.488684	29.525833
	30.336714	30.488791	30.274345	30.044127	30.114759
	30.231447	29.897984	29.887321	30.118811	30.159058
	30.248556	30.748699	30.836027	30.867603	31.170177
	31.291073	31.164534	31.121346	31.401297	31.351158
	31.284279	30.554182	30.42947	30.28661	30.278994
	30.39658	30.966383	26.127291	26.686211	26.647455
	26.366659	26.548807	26.381777	25.973215	26.587601
	26.546673	27.152704	28.123289	28.970297	29.18428
	31.053225	31.258579	31.379217	33.151478	32.845463
	31.498503	32.903831	33.682457	34.605389	34.718292
	31.408617	30.842836	29.973616	28.693377	28.798429
	29.586842	28.943041	27.799698	27.962872	28.090429
	27.15345	26.890577	26.687992	26.646816	27.005733
	26.94017	26.464012	26.577242	26.91848	26.941383
	26.77429	26.840322	26.819462	26.896212	26.830059
	26.898109	26.900316	26.883863	26.54423	26.574162

[0306]

[0307] Power-minimized scheme

[0308]	33.582207	33.95343	33.232883	32.875256	32.298672
	32.473114	32.254253	32.707806	31.50325	31.899975
	31.873747	31.893358	30.078756	30.448971	29.60833
	30.178741	29.794933	29.627445	30.451933	30.43856
	30.41687	30.952185	30.072472	30.350559	30.793671
	30.826012	29.850634	29.57519	29.290724	29.533686
	29.212015	29.505108	30.989365	31.225384	31.565819
	31.722179	31.2829	31.325502	31.559874	31.55839
	31.574083	31.457434	31.301744	30.686214	30.497229
	30.399715	31.018776	30.884525	31.075693	31.408024
	30.759403	31.505575	32.10014	30.843391	30.652742
	30.634027	31.440193	30.907139	30.470402	30.617229
	32.180904	32.516144	32.885113	33.992313	32.792919
	30.870892	31.965769	33.401531	34.485405	32.724659
	30.964081	30.146334	28.01515	27.555481	28.50741
	29.380953	27.173027	26.124149	26.292469	26.817856
	26.33288	26.125313	26.018761	26.012234	26.08577
	26.106392	26.002115	26.279865	26.233225	26.393005
	26.11652	26.258884	26.204458	26.372618	26.246414
	26.349415	26.342976	26.434429	26.199263	26.303782